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The Effect of Structures and Lake Level on Bluff and Shore Erosion in Berrien County, Michigan, 1970-74

by
William A. Birkemeier

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Rates of bluff recession and shoreline change along five 1.6-kilometer reaches located within Berrien County, Michigan, between 1970 and 1974 were measured by use of aerial photos. Annual measurements were made at 30.5-meter intervals, except for two adjacent reaches where biannual measurements were made. The overall average rate of recession for the five reaches was 3.8 meters per year. Average recession rate varied from 2.4 meters per year

Continued

for a reach with low foredunes to 4.5 meters per year along a reach with a high sandy bluff. The greatest amount of recession resulted from a significant storm occurring 16 to 18 March 1973.

Simple regression analysis of the data from both lake level and storm parameters identified storms as the primary cause of recession. However, the data set was too small and at such a unique point in the long-term lake level cycle (the crest of a rising peak) to quantify the effect of lake level.

The effect of a 579-meter-long seawall constructed during the study is discussed; the volume of material eroded downdrift of the wall nearly equaled the amount of material removed from the sediment supply by the seawall.

The procedures used in analyzing the air photos and their accuracy are described in an Appendix. Guidance is also given for determining the number of measurement points needed per distance along the shore depending on the desired accuracy of the bluff recession rates.

PREFACE

This report is published to improve the understanding of Great Lakes bluff recession and the factors controlling it. The report is the result of a study of a series of air photos taken between 1970 and 1974 of 8 kilometers of shoreline in Berrien County, Michigan. The work was carried out under the coastal processes program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by William A. Birkemeier, Hydraulic Engineer, under the supervision of Dr. C. Galvin, Jr. and C. Mason, Coastal Processes Branch, Research Division.

The author acknowledges the assistance of many CERC staff members, including S. Hildenbrandt for his painstaking collection of the data and review of the report; T.J. Lawler for developing some of the computer programs; K. Jacobs for aid in some of the data analysis; and Dr. D.L. Harris, C. Mason, A.E. DeWall, and E.B. Hands for their helpful reviews and comments which greatly benefited the report. Reviews by Dr. C.J. Galvin, Jr. (formerly of CERC), C. Johnson, U.S. Army Engineer Division, North Central (who originally suggested the study), R. Elkin, U.S. Army Engineer District, Detroit, and C. Kureth, The Traverse Group, Ann Arbor, Michigan, contributed greatly to improving and consolidating the final report.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

Wilson P. Andrews LTC
for TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

THE EFFECT OF STRUCTURES AND LAKE LEVEL ON BLUFF AND SHORE EROSION IN BERRIEN COUNTY, MICHIGAN, 1970-74

by
William A. Birkemeier

I. INTRODUCTION

The staggering loss of public and private property along the Great Lakes during the period of high lake levels, which peaked in 1973 and 1974, focused renewed interest on understanding the lakeshore erosion problem and on developing methods to minimize it.

This study examines, by use of aerial photos and other available data, the shoreline and bluff-line erosion which occurred along Berrien County, Michigan, between November 1970 and November 1974, a period of rising lake levels. A major emphasis of the study is the investigation of the spatial and temporal variation in bluff recession along both protected and unprotected shorelines. The effect of lake level is also discussed but the period covered by the data set is too short to adequately cover this phenomena.

1. Study Area.

The study area is located in the southeastern section of Lake Michigan near Stevensville, Michigan (Fig. 1). Shoreline use includes summer and permanent residences, undeveloped parkland, and the Donald C. Cook Nuclear Plant which was under construction during the study period. Five 1.6-kilometer reaches of shoreline were selected for study; three of the reaches (A, B, and C) are north and two (D and E) are south of the nuclear plant (see Fig. 1 for locations of each reach). Selection was based on bluff type, height, and local structures. The reaches were selected away from the powerplant to minimize the influence of the construction of a temporary harbor and an associated sand-bypassing project at the plant. The temporary harbor and its effect are discussed in Johnson and Hiipakka (1976). General characteristics of the study reaches are given in Table 1.

Reaches A and B form a continuous 3.3-kilometer stretch of shoreline composed of predominantly sand bluffs ranging from 3 to 15 meters in height. The

Table 1. General characteristics of study reaches.

Reach	Orientation	Length (km)	Beach width (m)	Bluff height (m)	Bluff type	Offshore slope[1]	Shore protection structures	Residences (No.)	Distance from nuclear powerplant (km)
A	N. 27° E.	1.71	4 to 8	10 to 15	Sand-till bluff	0.0073	Minor	11	7.7 N.
B	N. 26° E.	1.62	6 to 11	3 to 14	Sand-till bluff	0.0072	Major	28	6.0 N.
C	N. 26° E.	1.52	5 to 13	3 to 7	Sand foredune	0.0081	None	0	3.0 N.
D	N. 19° E.	1.62	2 to 9	3 to 7	Sand foredune	0.0095	Minor	33	3.0 S.
E	N. 30° E.	1.62	6 to 17	3 to 7	Sand foredune	0.0089	None	0	7.0 S.

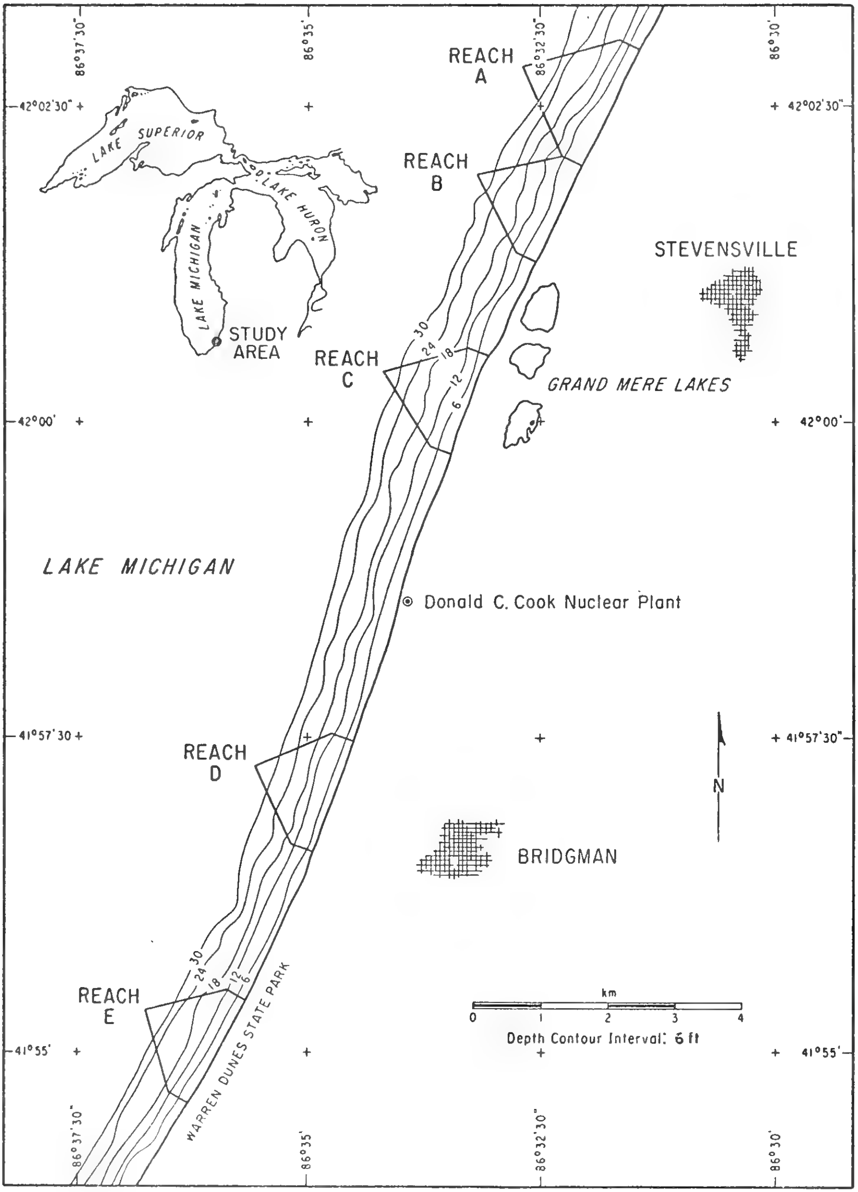

Figure 1. Location of study reaches.

primary difference between reaches A and B is a 579-meter-long seawall constructed in reach B during the study period. The two reaches were compared to determine the effect of the seawall on the surrounding shoreline.

Reaches, C, D, and E differ from A and B in that the active bluff line is composed primarily of low foredunes fronting a ridge which reaches heights of 36 meters above the mean lake level. Reaches C and E (on opposite sides of the powerplant) differ slightly in orientation and both are undeveloped; reach D is developed. None of these three reaches include any major shore protection structures.

2. Available Data.

The primary data used in this study were aerial photos taken monthly of the shoreline from July 1970 to December 1974. These photos were originally used to monitor the effects on the adjacent shoreline of the temporary harbor and the sand-bypassing project at the powerplant. Each photo set covered about 18 kilometers of shoreline centered around the nuclear powerplant. Nominal scale was 1:3,600 with 40 to 60 percent overlap for stereo viewing. The air photo analysis procedure and its accuracy are discussed in the Appendix.

Other data collected during the study period include (a) hourly wind measurements at the powerplant, (b) visual observations of daily wave and wind characteristics from Warren Dunes State Park (within reach E), and (c) monthly ground surveys of 17 eastern Lake Michigan profile lines (including profile line 16 in reach B collected by Davis, Fingleton, and Pritchett (1975), Davis (1976), and the U.S. Army Engineer District, Detroit).

Background data for the study area are presented in Section II. Section III discusses the data for each reach and the changes that occurred. Section IV compares the results, both between reaches and to the results of other Berrien County studies; speculation about the effects of lake level changes and storms on the rate of bluff recession and about the effects of seawalls on adjacent shorelines is also presented. A summary and recommendations for future studies are given in section V.

II. ENVIRONMENTAL CHARACTERISTICS OF THE STUDY AREA

Many important factors influence the rate of bluff and shoreline change. These factors can be divided into "shore factors" and "process factors." Shore factors include the shape, composition, and orientation of the beach and bluff, which are relatively easy to determine for any particular area. Process factors include the wind and wave climate, water level variations, and storm type and frequency which are not so easily determined. Secondary factors, such as ice cover and runoff, are also important.

1. Lake Levels.

The most widely discussed process factor affecting bluff recession is the fluctuation in lake level. Although a high proportion of bluff recession probably results from individual storms, lake level appears to be a controlling factor (Hough, 1958; Seibel, 1972; Maresca, 1975; Berg and Collinson, 1976).

This study covers the final 3 years of a steady 9-year period of increasing lake level from an annual mean of 175.49 meters, International Great Lakes Datum (IGLD), in 1964 to 176.92 meters in 1973. During 1974, the final year of study, the lake stabilized at a level just slightly less than the 1973 level. The variation in lake level from 1951 to 1974 as recorded by the National Oceanic and Atmospheric Administration (NOAA) (1971; 1972; 1973; 1974; 1975) is shown in Figure 2.

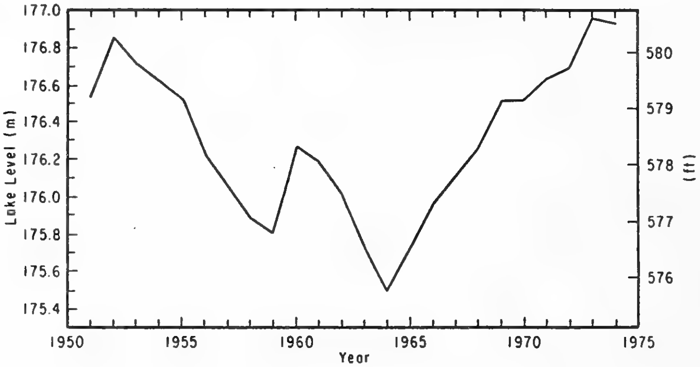

Figure 2. Annual average of Lake Michigan water level as recorded at Ludington, Michigan, from 1951 to 1974 (IGLD).

Figure 3 shows the mean monthly lake level from 1970 to 1974 and the maximum and minimum mean daily water levels for each month. The average seasonal lake level variation from lows in the beginning of the year to highs in summer is 0.34 meter which equals the long-term average given by Seibel (1972). A major increase in the average lake level occurred in 1972 when there was little seasonal decrease in lake level following the summer peaks.

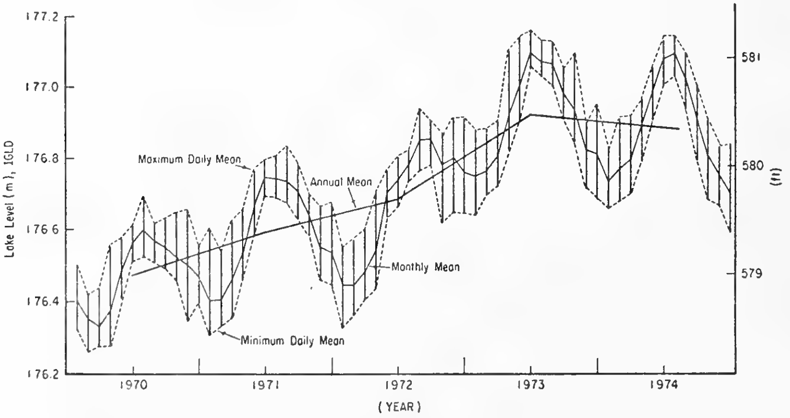

Figure 3. Monthly mean Lake Michigan water levels at Ludington, Michigan.

Assuming an idealized situation of a noneroding beach, an increase in water level would have a direct effect on the shoreline by causing an apparent "submergence" of the shore and an "encroachment" of the water over the land (Hands, 1979). Similarly, a lowering of the water level will cause an "emergence" of the shore and "withdrawal" of the water. The amount of encroachment or withdrawal depends on the slope of the beach and can be quite significant. For example, assuming a beach slope of 1:10, the seasonal lake level fluctuation of 0.34 meter will move the shoreline 3.4 meters, a significant amount on beaches which tend to be only 15 to 25 meters wide. At the peak lake level recorded in June 1973 (177.1 meters), submergence alone since 1964 could account for on the order of 16 meters of landward shoreline movement.

2. Waves.

Waves and wave-induced currents are the primary agents causing "erosion" (removal of material) and "accretion" (deposition of material). The wave climate at a particular site depends on the wind climate, the fetch, the orientation of the shoreline, and the bottom bathymetry. The only wave data available for the study area are daily visual observations collected at Warren Dunes State Park (reach E) under the CERC Littoral Environment Observation Program (LEO). Some of the data and a discussion of the LEO program are presented in Bruno and Hiipakka (1973). A summary of the breaking wave characteristics is given in Table 2. Since visual data are somewhat subjective and observer-dependent, its accuracy is unknown. The average values do, however, compare favorably with similar data collected at other eastern Lake Michigan locations.

The average monthly wave height increases from minimum values in the summer to high values in late fall and early spring. The average wave height is only 0.47 meter but waves as high as 1.8 meters have been observed. As expected, the restricted fetch due to the lake boundaries causes wave periods to be short (4.1 seconds on the average); however, a 9-second wave was observed.

Table 2. Summary of visual breaking wave data at Warren Dunes State Park, 26 October 1971 to 4 December 1974.

Month	Wave height		Wave period		Observations
	Avg. (m)	Peak (m)	Avg. (s)	Range (s)	
Jan.	----[1]	---	---	----------	--
Feb.	----	---	---	----------	--
Mar.	0.51	1.1	4.6	3.0 to 5.9	18
Apr.	0.43	1.4	4.4	2.9 to 7.0	63
May	0.35	1.1	3.9	2.5 to 6.7	57
June	0.41	1.4	3.5	1.5 to 9.0	69
July	0.37	1.5	3.2	1.6 to 5.8	81
Aug.	0.37	1.4	3.4	1.8 to 6.5	81
Sept.	0.51	1.3	4.2	1.5 to 6.7	50
Oct.	0.50	1.8	4.1	1.5 to 7.0	70
Nov.	0.62	1.5	4.4	2.0 to 7.0	92
Dec.	0.66	1.5	4.8	1.0 to 6.6	51
Yearly	0.47	1.8	4.1	1.0 to 9.0	632

[1] No data due to ice cover.

NOTE.--Averages include calm periods; range of wave periods does not. Data represent 68 percent of the 931 possible observations during the period (not including periods of ice cover).

Because of its location, fetch is an important factor in the wave climate of the area. The fetch varies from about 400 kilometers to the north, to only 60 kilometers to the southwest.

The effect of fetch is also shown by the hindcasted design wave characteristics given for the study area in Resio and Vincent (1976). They determined design wave heights and periods for waves from three directions (shore-normal, and greater than 30° to the right and to the left) for each season, and for return periods of 5, 10, 20, 50, and 100 years. For example, using the 50-year return period and the winter season, the deepwater design wave heights are given in Table 3. As expected, the largest waves are along the longest fetch. Interestingly, the characteristics of the design storm and the hydrography are such that waves normal to the beach (west-southwest to northwest) will be nearly as high as waves from the longest fetch, while the waves along the shortest fetch will be significantly lower.

Table 3. Winter deepwater design waves for a 50-year storm.

Wave direction	Height (m)	Period (s)	Avg. fetch (km)
NW. to NNE.	6.6	11.4	280
WSW. to NW.	6.0	10.7	118
SW. to WSW.	2.8	7.3	80

Because the wave characteristics in Table 3 are for deepwater conditions and for extreme events (with a probability of occurrence once every 50 years), they are significantly different from the average breaking conditions in Table 2.

3. Storms.

The low-pressure storm systems which affect the study area generally move through the Great Lakes from west to east. The combination of this path and counter-clockwise circulation around the low center produces strong winds from the north and northwest usually following passage of the storm. Seibel (1972), Maresca (1975), and Davis (1976) have investigated the wind and wave climate of the study area and the characteristics of the storms which affect the eastern shore of Lake Michigan.

Seibel (1972) determined that the annual number of low-pressure systems passing through the Great Lakes between 1938 and 1970 averaged about 43, though the number varied from 31 to 67. The number of storms did not appear as important in determining bluff recession as the intensity of individual storms.

Although many storms occurred between November 1970 and November 1974, one of the most significant storms occurred 16 to 18 March 1973. The storm caused some of the highest winds of the study period with windspeeds at Muskegon, Michigan, averaging 41 kilometers per hour from the northwest for 2 days. At the powerplant, an anemometer recorded windspeeds as high as 72.4 kilometers per hour. The highest recession rates measured during this study occurred at reaches A and B during 16 November 1972 to 20 March 1973 (just 2 days after the

March 1973 storm). Most of this change is attributed to the single storm, a fact supported by Johnson and Hiipakka (1976) who noted the severity of the 1972-73 storm season and its effect on bluff erosion near the powerplant. Davis (1976) reported that between August 1970 and July 1973 the largest total monthly change occurred between 11 March and 14 April 1973.

4. Littoral Material and Transport.

Littoral material is supplied by the eroding bluffs and dunes. Depending on bluff type, only 20 to 49 percent of the eroded bluff material is suitable beach material (Beach Erosion Board, 1956). Beaches are composed of fine quartz sand (diameter between 0.20 and 0.30 millimeter) with occasional deposits of heavy minerals and gravel.

The estimated net littoral transport rate for St. Joseph Harbor (north of the study area) equaled 76,460 cubic meters (100,000 cubic yards) per year (Beach Erosion Board, 1956). This estimate was based on profile changes (from the bluff to the 6-meter depth contour) and on the volume trapped by the harbor jetties between 1907 and 1954. A subsequent study by the U.S. Army Engineer District, Detroit (1973) updated the data but quoted the same transport rate which was also the amount of material required by the Detroit District to nourish the beach to the south of the powerplant.

Although the net direction of longshore transport is to the south, reversals are common. Visual observations of wave climate since 1974 indicate that about 32 percent of the gross transport moves to the north. This is not unexpected since Seibel (1972), using wind data from Muskegon, Michigan, showed that the direction of onshore winds shifts during the year. In summer the winds are generally from the southwest quadrant; in winter the winds are from the northwest where the fetch is longest.

5. Ice.

Lakeshore ice controls the amount of bluff recession by protecting the shore during January, February, and part of March. This is evident in an aerial photo taken 16 February 1972 of reach B (Fig. 4), which shows a maximum of 120 meters of solid ice bordering the shoreline. A thorough analysis of the development, buildup, and eventual disappearance of shore ice over the winter of 1973-74 was done by Seibel, Carlson, and Maresca (1975) in conjunction with the construction of the Donald C. Cook Nuclear Plant.

To compute bluff recession rates based on the assumption that no recession occurs during the period of ice cover (Davis, 1976), it was necessary to estimate when protective ice developed and disappeared using aerial photos and ice maps published by the Lake Survey Center, NOAA (Assel, 1972a, 1972b, 1974a, 1974b). The results given below (and used in Section IV,3) are considered the best estimates of ice-cover periods from November 1970 to November 1974.

30 December 1970	to	14 March 1971
5 January 1972	to	20 March 1972
29 December 1972	to	9 March 1973
5 January 1974	to	6 March 1974

Figure 4. Aerial view of lakeshore ice along reach B, 16 February 1972.

III. AIR PHOTO MEASUREMENTS

1. Data Collection.

Procedures used in obtaining measurements and in estimating the amount of measurement error are described in the Appendix to this report. The basic data collection procedure was to measure the position of the bluff line or crest, bluff toe, and shoreline at "stations" located every 30.5 meters (100 feet) along each reach. All features were identified by stereoscopic viewing of the photos. "Bluff crest" was defined as the landwardmost edge of active erosion, "bluff toe" as the point separating the steep bluff and flat beach, and "shoreline" as the water's edge. Measurements for reaches A and B were taken from nine sets of photos between November 1970 and November 1974 at about 6-month intervals. Data from reaches C, D, and E were collected from five sets of photos at 1-year intervals.

Because monthly sets of photos were available, it was possible to be selective in choosing the photos for analysis. Selection was based on the amount of ground vegetation, the relative positions of the bluff line to the center of the photos, shadows, ice cover, and scale variation.

To avoid the problem of vegetation obscuring much of the bluff crest, photos taken in early spring and late fall were chosen. This selection also separated, to some extent, the stormy winter season of October to April. Where possible, March and November photos were used. Dates and scales of the photos used for analysis in each reach are listed in Table 4; the average daily lake level on the day the photos were taken is also included.

Table 4. List of aerial photos.

Reach	Date	Lake level[1] (m)	Photos (No.)	Scale range[2]
A,B	19 Nov. 1970	176.46	CY00493 to CY00502	0.979 to 1.048
	15 Apr. 1971	176.54	CY00809 to CY00813	1.005 to 1.034
	16 Nov. 1971	176.54	CY01277 to CY01281	0.976 to 1.002
	18 Apr. 1972	176.55	CY01619 to CY01623	0.985 to 1.018
	16 Nov. 1972	176.80	CY02120 to CY02125	1.020 to 1.062
	20 Mar. 1973	176.88	CY02387 to CY02391	1.004 to 1.038
	20 Nov. 1973	176.81	CY02958 to CY02963	0.936 to 0.976
	20 May 1974	177.06	CY03365 to CY03369	0.980 to 1.053
	23 Nov. 1974	176.73	CY03769 to CY03773	1.000
C	15 Apr. 1971	176.54	CY00818 to CY00824	1.028 to 1.045
	22 Dec. 1971	176.45	CY01351 to CY01355	1.000 to 1.002
	16 Nov. 1972	176.80	CY02130 to CY02134	1.028 to 1.073
	18 Oct. 1973	176.94	CY02895 to CY02899	1.064 to 1.078
	23 Nov. 1974	176.73	CY03778 to CY03783	1.000
D	19 Nov. 1970	176.46	CY00527 to CY00532	1.010 to 1.053
	15 Apr. 1971	176.54	CY00838 to CY00842	1.021 to 1.048
	16 Nov. 1972	176.80	CY02149 to CY02154	1.056 to 1.080
	18 Oct. 1973	176.94	CY02912 to CY02916	1.055 to 1.070
	23 Nov. 1974	176.73	CY03798 to CY03803	1.000
E	15 Apr. 1971	176.54	CY00851 to CY00855	0.993 to 1.040
	16 Nov. 1971	176.54	CY01318 to CY01322	0.965 to 0.986
	16 Nov. 1972	176.80	CY02161 to CY02166	1.060 to 1.071
	20 Nov. 1973	176.81	CY03001 to CY03006	0.960 to 0.980
	23 Nov. 1974	176.73	CY03812 to CY03815	1.000

[1] Average daily lake level on day photo was taken.

[2] Range in scales of individual photos relative to the scale of the November 1974 photos (assumed 1:3,6000); see Appendix.

NOTE.--Photo copies are available from Abrams Aerial, Lansing, Michigan, 48901.

Measurements were tabulated and amounts of change were computed with the aid of a computer program. The estimated accuracy of a bluff position measurement for a single station is ±0.91 meter (see computations in App.). A change in bluff position can be measured to an estimated accuracy of ±1.4 meters. The accuracy of average changes and rates determined over all the stations in a reach is dependent on the number of measurement points and the standard deviation of the measured values. Since collecting data from photo imagery is tedious, only as few measurements as possible should be made. The problem of estimating how many measurements to take is discussed in the Appendix.

Because of the increased problems with parallax (see App.), greater daily variability, changing lake levels, and measurement point identification, measurements of the shoreline and the bluff toe were less accurate than measurements of the bluff crest. To reduce the effect of emergence and submergence, shoreline measurements were corrected to an average lake level using the measured lake levels, for the day each photo was taken and an approximate foreshore slope (generally 0.1; foreshore slope was estimated from monthly surveys of profile lines near the powerplant and of CERC profile line 16 within reach B (Davis, Fingleton, and Pritchett, 1975)). This correction was not made where the shoreline was constrained by a vertical shore-parallel structure.

Annual rates of change were computed for both the shore and bluff lines for each period based on period length. Although this provides some comparison of changes between periods of varying length (4 to 19 months), it can be misleading, particularly for periods shorter than 1 year and for winter periods when actual changes are restricted to ice-free periods (the effect of computing rates based on the ice-free period is discussed in Section IV,3).

Any recession rate measurement taken out of context may be somewhat misleading. For instance, if an area retreated 6 meters during one storm, with no other recession during the year, the annual retreat rate is 6 meters per year. If, however, monthly measurements were made, the annual retreat rate for the storm month is 72 meters per year while the retreat rate for the remaining 11 months would be zero. The retreat rate over the full 12 months would, of course, still be 6 meters per year. To avoid possible confusion, comparisons should be made of rates determined for similar or nearly similar time periods. Because of the seasonal nature of Great Lakes processes, annual rates (regardless of ice-cover periods) are the most logical. However, the rates must be based on data covering a period greater than 1 year to be useful.

To minimize confusion in this study, the actual amounts of change for each period along with the rates have been tabulated for each reach. Annual changes have also been computed by combining 6-month periods.

2. Reach A.

Reach A (Fig. 5), extends for 1.71 kilometers and includes 57 measurement stations. It covers a stretch of high, lightly developed bluff which has undergone extensive erosion. Only four shore protection structures are within the reach, and all include seawalls built before 1970. Although the structures offered some localized protection, the bluff continued to erode behind them. Some of the most dramatic erosion occurred at the northern end of the reach (Fig. 6) where at least one house toppled over the bluff.

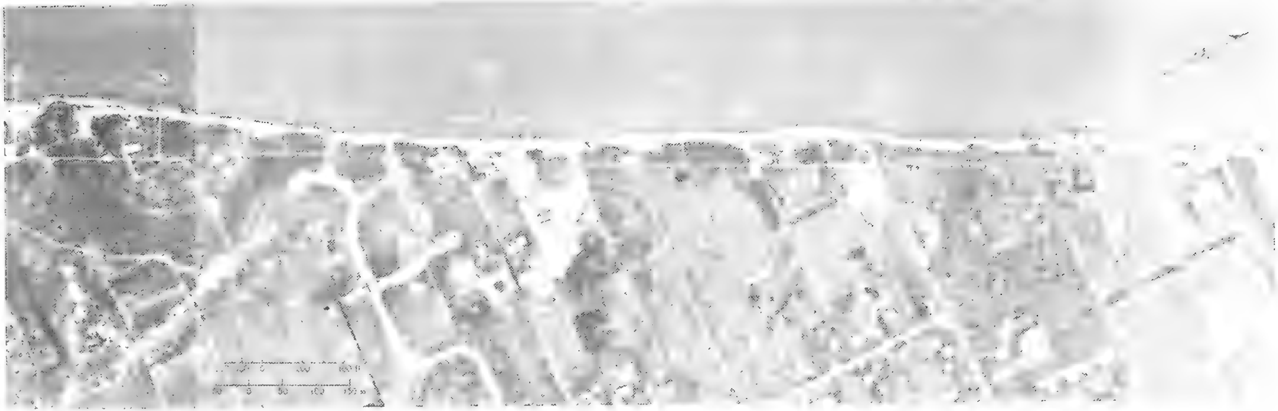

Figure 5. Composite aerial photo of reach A taken 23 November 1974. Arrows indicate the location of shore protection structures; numbers are measurement stations.

Figure 6. Severe bluff erosion at the northern end of reach A. Structures shown are located at stations 110 and 105. Photo taken 16 October 1976.

The variation in the rate of bluff recession and shoreline change (defined as the effect of all processes except submergence and emergence) is plotted in Figure 7 for the eight periods examined.

A feature of Figure 7 and all the other data plots is the sawtooth pattern of the plotted line. This sawtooth shape may have a magnitude of from 1.5 to 4.6 meters per year and can be attributed to a combination of analysis error and to actual changes between adjacent stations. No attempt has been made to either further refine the analysis or to smooth the raw data. The data clearly exhibit trends along the reach and these trends are more significant than individual station measurements.

Although measurements of shoreline change are less accurate than those of bluffs, some of the trends in the shoreline change appear significant. Shoreline changes tended to have a greater range (factor of 2) and a higher degree of variability than the bluff recession changes.

In general, the winter to spring time periods had higher rates of recession than the spring to winter periods. The highest short-term rate of recession occurred during 16 November 1972 to 20 March 1973 when an average loss of 2.6 meters was measured during the 4-month period (which included more than 2 months of ice cover) for a rate of 7.6 meters per year. The peak recession of 10.7 meters occurred during this period at station 105 when a house toppled down the bluff. Most of the recession occurred between stations 85 and 107, a trend which began during the 18 April to 16 November 1972 period. Before this period, the recession was more uniformly distributed along the reach. The mean recession rate and the standard deviation for each period were found to be positively correlated, indicating that as the mean recession rate increased, so did the amount of variation in the rate along the shore. The highest rate of shoreline change (a retreat of 20 meters) occurred at station 100 between 16 November 1971 and 18 April 1972, a 5-month period. During the same period, except for two stations, the entire shoreline retreated. No significant correlation was found between the bluff and shoreline changes; however, the lowest rate of bluff recession occurred between 15 April and 16 November 1971 when the shoreline experienced the greatest accretion, and the average "beach width" (defined as the distance between the shoreline and the bluff toe) increased 4.3 meters.

Overall rates of bluff recession and shoreline change for the 4-year period are shown in Figure 8. The average bluff recession rate of 4.6 meters per year slightly exceeded the average shoreline retreat rate of -3.2 meters per year. The greatest amount of shoreline change occurred in the same relative area as the highest bluff recession, between stations 95 and 105.

Because of the difficulty in identifying the toe of the bluff, plots of beach width are not shown. Beach widths were generally narrow during the study, averaging 5 to 12 meters. The beach width at individual stations varied from zero to a maximum of only 24 meters.

Of the five reaches, reach A experienced the highest average rate of bluff recession. Data for the eight time periods and 57 stations are summarized in Table 5. Because no major shoreline structures are in reach A it is an ideal area to examine the relationships between the bluff recession, storm frequency, and lake level. The results of the analysis of these variables are discussed in Section IV.

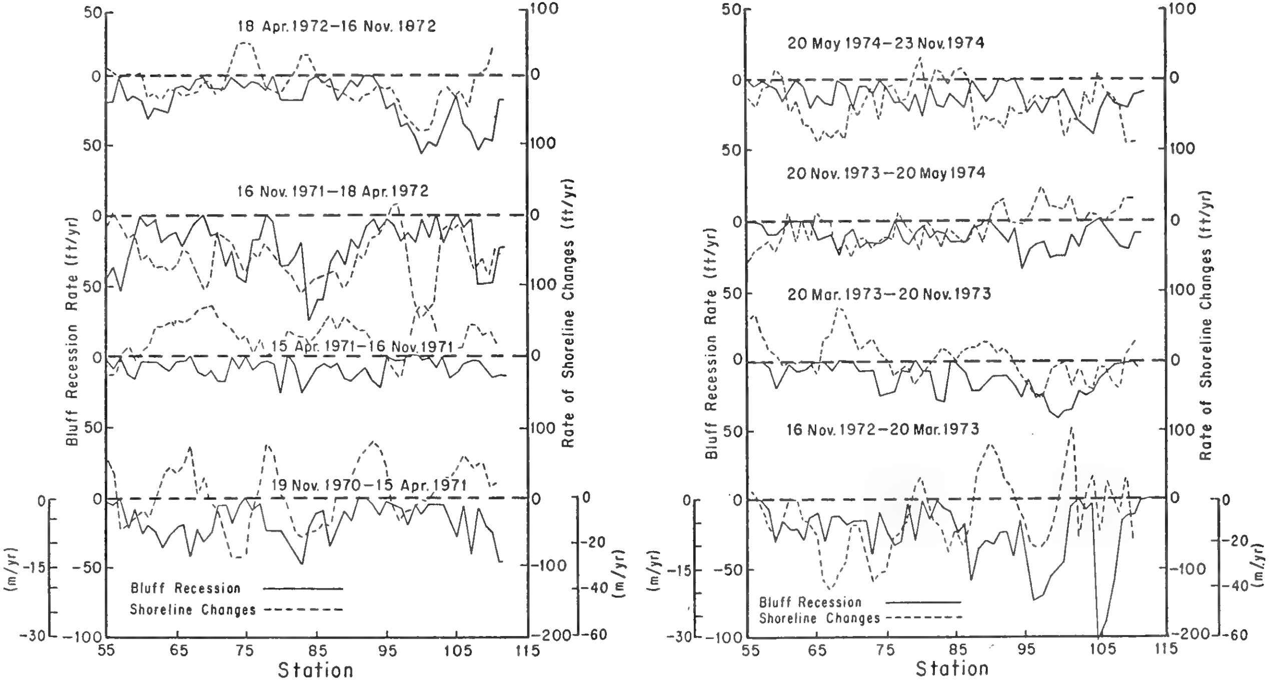

Figure 7. Rates of bluff recession and shoreline change along reach A (note different vertical scales). Negative values indicate landward movement of the bluff and shore lines. See Figure 5 for numbers identifying measurement stations.

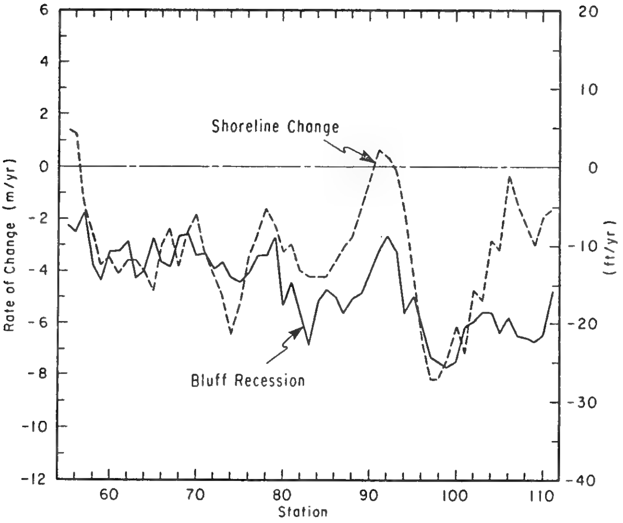

Figure 8. Rates of bluff recession and shoreline change along reach A from 19 November 1970 to 23 November 1974.

Table 5. Summary of bluff, shore, and beach data for reach A (57 stations).

Date	Bluff recession				Shoreline change				Beach width[1]			Period length
	(m)	Rate (m/yr)	σ (m/yr)	Max. (m/yr)	(m)	Rate (m/yr)	σ (m/yr)	Max. (m/yr)	(m)	σ (m)	Change (m)	(mo.)
19 Nov. 1970									4.3	4.6		
	2.2	5.2	3.9	14.6	0.9	2.3	13.5	-25.9				5
15 Apr. 1971									5.5	3.4	1.2	
	1.4	2.5	2.1	7.8	5.0	8.6	7.9	23.1				7
16 Nov. 1971									9.8	4.7	4.3	
	2.8	6.7	5.5	22.7	-8.0	-19.3	11.5	-47.5				5
18 Apr. 1972									8.3	3.3	-1.5	
	3.2	5.5	4.9	16.7	-2.7	-4.7	9.0	-25.8				7
16 Nov. 1972									5.3	3.5	-3.0	
	2.5	7.6	7.1	32.0	-2.6	-7.8	16.4	-39.8				4
20 Mar. 1973									5.5	4.2	0.2	
	2.6	3.9	3.5	12.8	0.8	1.2	9.2	23.9				8
20 Nov. 1973									6.8	4.6	1.3	
	1.7	3.5	2.5	10.4	-1.2	-2.3	7.4	-16.6				6
20 May 1974									7.2	4.8	0.4	
	1.9	3.8	2.8	12.2	-5.1	-10.3	9.8	-28.0				6
23 Nov. 1974									8.0	4.9	0.8	
19 Nov. 1970									4.3	4.6		
	3.6	3.6	2.2	10.7	5.9	5.9	7.0	19.8				12
16 Nov. 1971									9.8	4.7	5.5	
	6.0	6.0	3.4	15.8	-10.7	-10.7	7.7	-34.8				12
16 Nov. 1972									5.3	3.5	-4.5	
	5.2	5.2	3.8	13.7	-1.8	-1.8	7.3	-18.0				12
20 Nov. 1973									6.8	4.6	1.5	
	3.6	3.6	1.9	7.6	-6.3	-6.3	4.9	-18.0				12
23 Nov. 1974									8.0	4.9	1.2	
19 Nov. 1970 to 23 Nov. 1974	18.4	4.6	1.5	7.6	-12.9	-3.2	2.1	-8.1				48

[1] Beach width adjusted to lake level (176.79 meters, IGLD).

3. Reach B.

Reach B (Fig. 9) extends 1.62 kilometers from the southern edge of reach A to the Chalet on the Lake housing development. The sand bluff decreases in elevation from about 15 meters at the northern end to less than 3 meters at the southern end. Except for reach D, reach B is the most heavily developed reach with 28 houses, one-half of which are between stations 22 and 42 where a 579-meter-long seawall was constructed during the study. The sequence of development of the seawall is important in understanding the changes that occurred along reach B.

To facilitate analysis, reach B is divided into five areas. Station 13 (Fig. 10) is approximately the same location as CERC profile line 16 discussed by Davis, Fingleton, and Pritchett (1975) and Davis (1976). The section between stations 14 and 22, referred to as the "downdrift cut," is located immediately downdrift (south) of the long seawall (Fig. 11) which protects the shoreline between stations 23 and 41. North of the seawall, between stations 42 and 46, is a high, unprotected and lightly vegetated sand dune (Fig. 12). Two smaller seawalls, one 91 meters long between stations 47 and 50 and one 30 meters long at station 54, are in the northern end of the reach. Both of these seawalls were constructed before the beginning of this study.

Figure 13 shows reach B as it appeared in November 1970. Note the absence of a beach in front of the sand dune area. A beach averaging 11 meters wide fronts the seawall area; a similarly wide beach also fronts the downdrift stations. The shoreline is straight from the 91-meter seawall southward. The existence of two seawalls at the bluff toe in the area where the long seawall will be built is an indication of previous erosion.

Figure 14 shows the rates of bluff recession and shoreline change along the reach for the same time periods as reach A. Vertical lines separate the areas shown in Figure 12.

During the first period, November 1970 to April 1971, the average bluff recession rate for the full reach was 4.3 meters per year. However, most of the recession occurred in two areas of the reach--the dune area between stations 40 and 47 and the area between stations 21 and 27. By April 1971, construction of a concrete seawall had started in the vicinity of station 32. The width of the beach gradually increased from zero at the northern end of the reach to about 14 meters at the southern end.

Construction of the full length of the seawall was completed by November 1971, though not in the final steel sheet-pile form. Bluff recession was moderate from April to November 1971, averaging only 1.1 meters with the dune section retreating the most. Beaches had narrowed in front of the seawall while a beach up to 30 meters wide appeared in front of the dune.

Major changes occurred between November 1971 and April 1972. The beach in front of the dune disappeared along with 8 meters of the dune bluff. The bluff behind the seawall retreated less than the dune area and the downdrift cut began to form. The bluff near station 13, south of the cut, was unchanged probably due to the relatively wide beach between stations 1 and 16. The average recession rate for the reach was 6.8 meters per year.

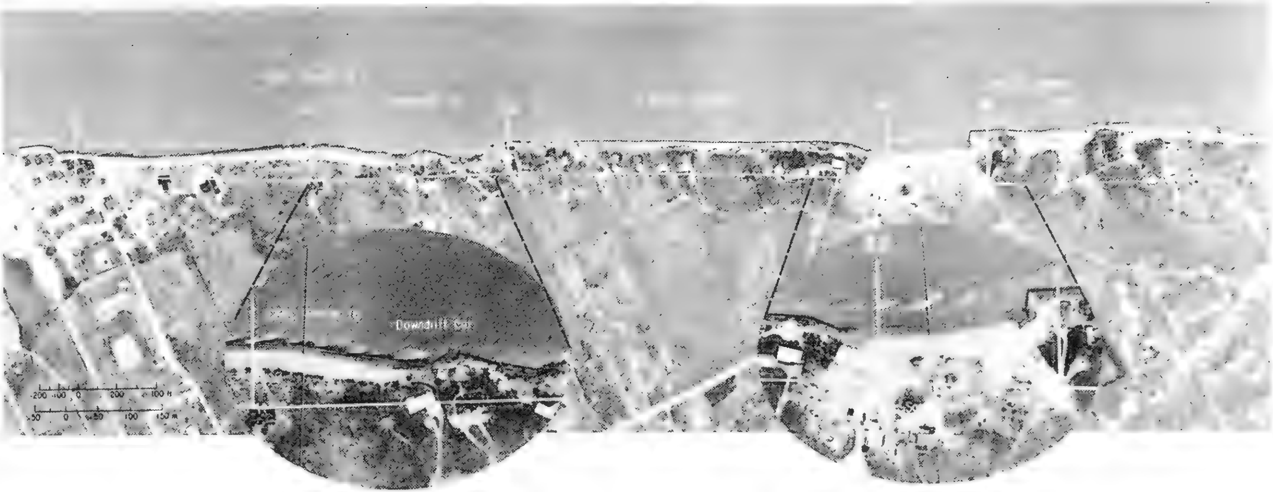

Figure 9. Composite aerial photo taken 23 November 1974 showing reach B with main sections identified. Inlets show details of dune and downdrift cut; arrows identify shore protection structures.

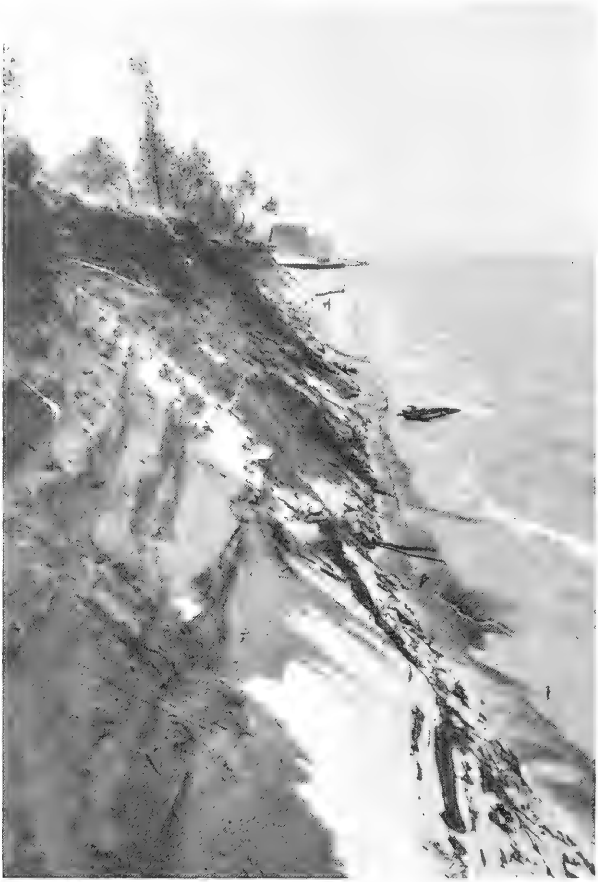

Figure 10. View southward from station 13 (also CERC profile line 16 in Davis, Fingleton, and Pritchett, 1975, and Davis, 1976). Photo taken 8 May 1976.

Figure 11. View southward from station 28 along the seawall (16 October 1976).

Figure 12. View northward from station 42 showing the dune section north of the seawall (16 October 1976).

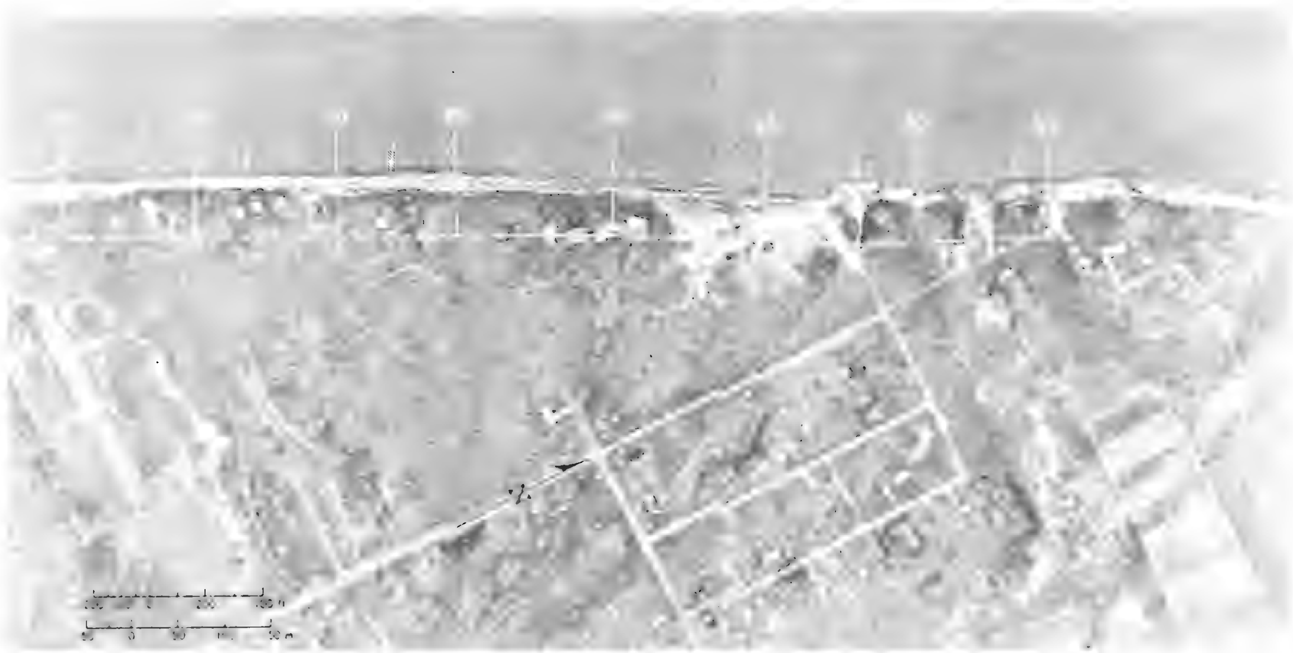

Figure 13. Composite aerial photo of the northern section of reach B taken 19 November 1970. Arrows indicate existing seawalls.

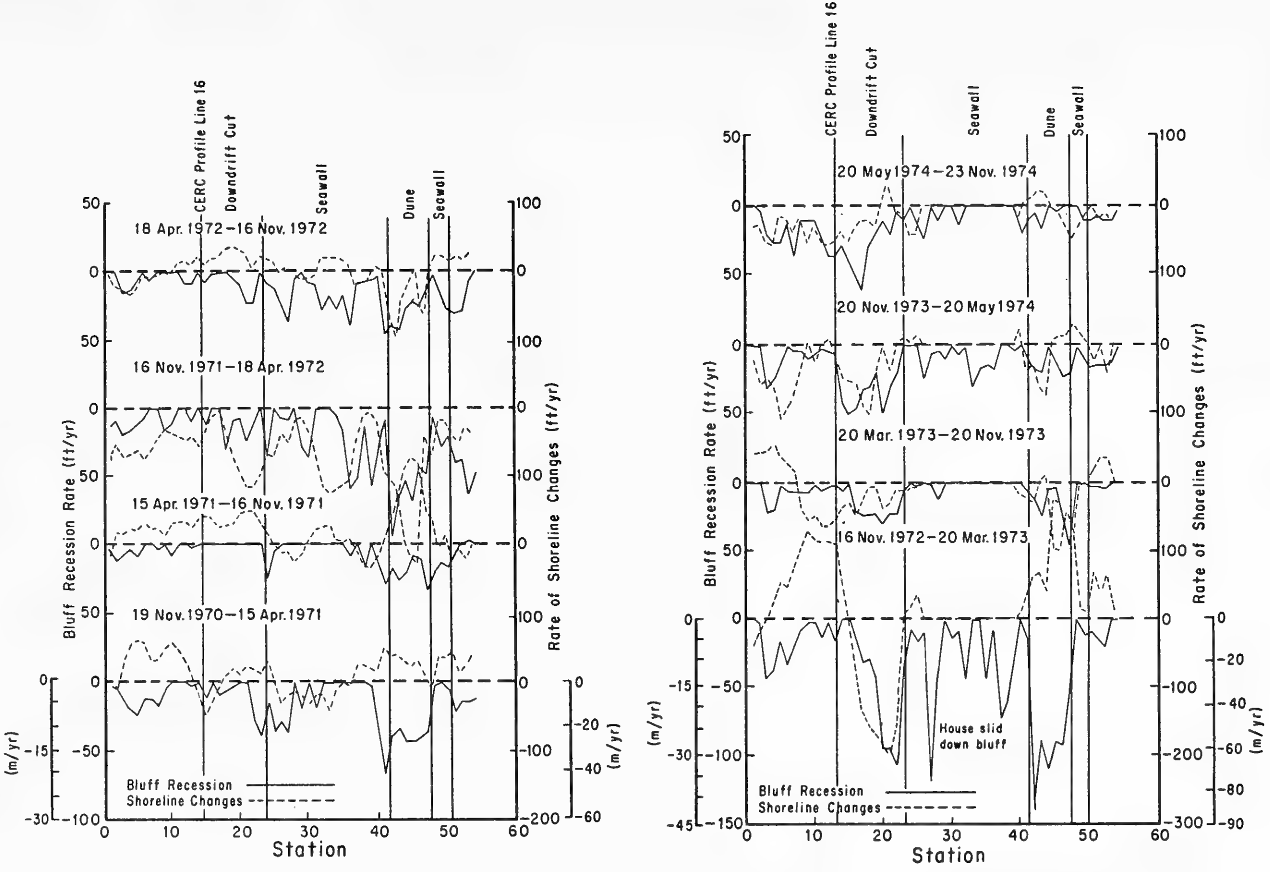

Figure 14. Rates of bluff recession and shoreline changes along reach B. Note different vertical scales.

The rate of bluff recession decreased between April and November 1972, to only 4.1 meters per year. The recession rate increased south to north with the southern end and some sections behind the seawall experiencing the least change. Figure 15 shows the reach between stations 35 and 13 in November 1972. The seawall is composed of steel sheet pile from station 28 to the northern end. From station 23 to 28 the beach is protected by the older and lower concrete wall behind which is evidence of recent bluff erosion. No beach exists lakeward of the seawall. The first evidence of a beach appears at station 24; a narrow beach also fronts the dune.

The most serious erosion occurred from November 1972 to March 1973 due to the intensity of the early spring storm (see Section II,3). The average rate of bluff recession during the period reached 10.1 meters per year for reach B. The bluff at station 42 retreated 14 meters. The seawall, completed during this period, did not fully protect the bluff behind it as evidenced by one small building which toppled down the bluff causing considerable recession at station 27. During this period the downdrift cut became better defined, extending from station 22 to about station 15. The bluff at station 22 retreated 11 meters. No beach was within the downdrift cut, though south of it the beach widened quickly to a maximum width of 23 meters at station 13.

Bluff recession continued at a reduced rate during the final three periods of study. The rate of bluff recession was the lowest behind the seawall and along the dune. However, the bluff at the downdrift cut was actively retreating, and the cut appeared to be lengthening (see the November 1973 photo in Fig. 15). The exact effects of the seawall on the bluff downdrift are difficult to fully assess because of seawall construction within the cut. This resulted in the formation of a second cut, to the south of the first (see the November 1974 photos in Fig. 9).

The sequence of events described above is illustrated in Figure 16. Average recession rates for each area are plotted in the figure, and compared with the rate for reach A since it represents the unprotected bluff recession rate. Variations in lake level are also shown. The reach A recession rate increased during the period of rising lake levels and then stabilized at a lower rate when the lake levels stabilized in 1974 (not including the usual seasonal variations). This stability may be attributed to other factors, particularly to the absence of severe storms in 1974. The dune section experienced a dramatic reduction in bluff recession rate after November 1973 which followed an equally dramatic period of erosion. The unstable areas were the downdrift cut and CERC profile line 16 (station 13). The downdrift cut shows a decrease in recession rate in November 1974, probably due to efforts to stabilize the area. These same measures probably accentuated the problem at CERC profile line 16 and farther south. The increase in recession was verified by ground surveys which measured an increase in bluff recession from 1.8 meters (Davis, 1976) between August 1970 and July 1973 to 9.4 meters between October 1973 and November 1974 (Birkemeier, in preparation 1980).

The downdrift erosion has continued; however, an October 1976 field visit found the bluff slope in the cut area well vegetated and stabilized (Fig. 17) and the bluff at CERC profile line 16 stabilized by the installation of a precast concrete seawall (Fig. 18). Measurements at CERC profile line 16 indicated an additional 9 meters of recession since November 1974. The bluff

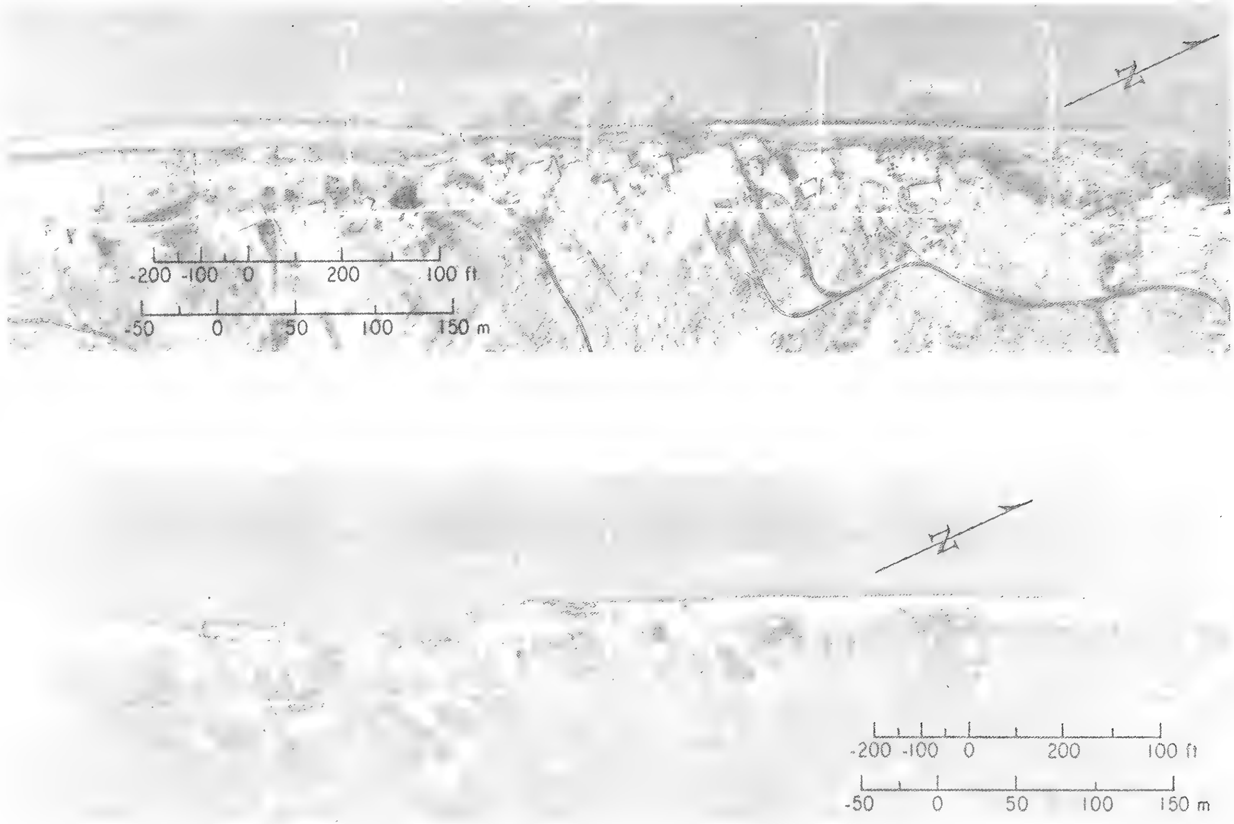

Figure 15. Aerial photos showing development of the downdrift cut south of the seawall from 16 November 1972 (top) to 20 November 1973 (bottom). See Figure 9 for November 1974 condition.

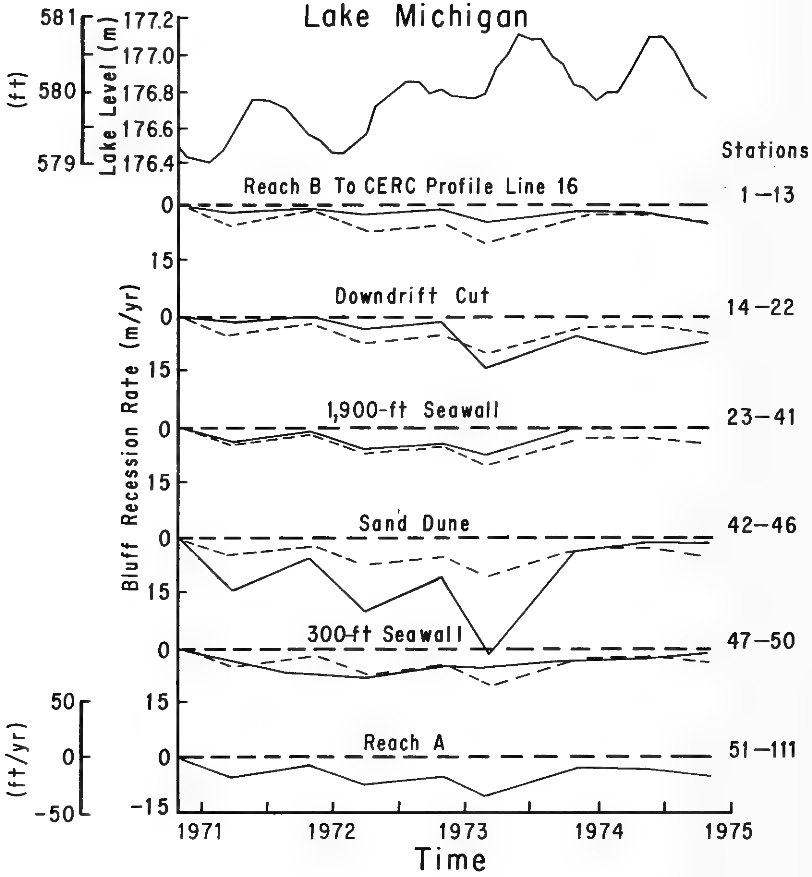

Figure 16. Variations in recession rate for different sections in reaches A and B compared to reach A (dashline).

Figure 17. View of the downdrift cut from the southern end of the seawall. Heavy vegetation on the bluff slope indicates successful stabilization (16 October 1976).

Figure 18. Bluff at CERC profile line 16 recently stabilized by precast-concrete seawall following a period of severe erosion (16 October 1976).

between stations 1 and 13 was also retreating despite a series of new sandbag groins. Probable explanations for the dramatic changes of the dune and for the downdrift cut are given in Section IV,4.

Overall rates of bluff and shoreline change for the full period of study are shown in Figure 19. Data measured from the air photos are summarized in Table 6. The table is based on simple averaging of all the stations in reach B and does not separate the protected and unprotected sections of shoreline.

Table 6. Summary of bluff, shore, and beach data for reach B (54 stations).

Date	Bluff recession				Shoreline change				Beach width[1]			Period length
	(m)	Rate (m/yr)	σ (m/yr)	Max. (m/yr)	(m)	Rate (m/yr)	σ (m/yr)	Max. (m/yr)	(m)	σ (m)	Change (m)	(mo)
19 Nov. 1970									6.2	5.7		
	1.8	4.3	4.9	20.5	1.9	4.5	8.6	19.5				5
15 Apr. 1971									7.6	4.2	1.4	
	1.1	1.8	2.7	10.5	3.7	6.3	10.1	38.1				7
16 Nov. 1971									10.6	5.8	3.0	
	2.8	6.8	7.0	29.3	-8.4	-20.2	15.2	-70.0				5
18 Apr. 1972									6.7	5.0	-3.9	
	2.4	4.1	4.0	14.1	0.4	0.6	7.9	-29.0				7
16 Nov. 1972									8.7	5.5	2.0	
	3.4	10.1	11.4	43.0	1.6	4.7	25.5	-63.6				4
20 Mar. 1973									12.1	6.1	3.4	
	1.5	2.3	3.1	13.7	-2.3	-3.5	10.5	-30.7				8
20 Nov. 1973									10.7	6.9	-1.4	
	2.0	4.0	4.2	15.2	-3.0	-5.9	10.5	-32.8				6
20 May 1974									9.7	4.7	-1.0	
	1.9	3.9	4.3	18.3	-2.6	-5.3	6.7	-17.7				6
23 Nov. 1974									8.2	4.4	-1.5	
19 Nov. 1970									6.2	5.7		
	2.9	2.9	3.1	13.7	5.6	5.6	7.3	25.8				12
16 Nov. 1971									10.6	5.8	4.4	
	5.2	5.2	4.4	19.2	-8.0	-8.0	8.4	-32.8				12
16 Nov. 1972									8.7	5.5	-1.9	
	4.9	4.9	5.1	17.1	-0.7	-0.7	9.2	-27.4				12
20 Nov. 1973									10.7	6.9	2.0	
	3.9	3.9	3.6	14.6	-5.6	-5.6	6.2	-18.9				12
23 Nov. 1974									8.2	4.4	-2.5	
19 Nov. 1970 to 23 Nov. 1974	16.9	4.2	2.6	11.9	-8.9	-2.2	2.2	-7.1				48

[1] Beach width adjusted to lake level (176.79 meters, IGLD).

4. Reach C.

Reach C extends for 1.52 kilometers southward from the last cluster of homes near the Grand Mere Lakes (Fig. 20). No houses are within the reach. The geomorphology of reach C differs from reaches A and B because of a low foredune (Fig. 21) which fronts and protects a high, well-vegetated dune ridge.

To keep definitions consistent, the term bluff line used in this discussion refers to the active edge of the foredune system. The bluff line could be determined by stereoscopic viewing but identification was more difficult than the bluff line in reaches A and B. Because of the lack of cultural features, it was also difficult to establish reference points and to match successive air photos.

Only reach C of the five reaches showed any lakeward movement of the bluff line due to foredune accretion. All of the accretion occurred south of the bend in the orientation of the shoreline between stations 20 and 30 (see Fig. 20).

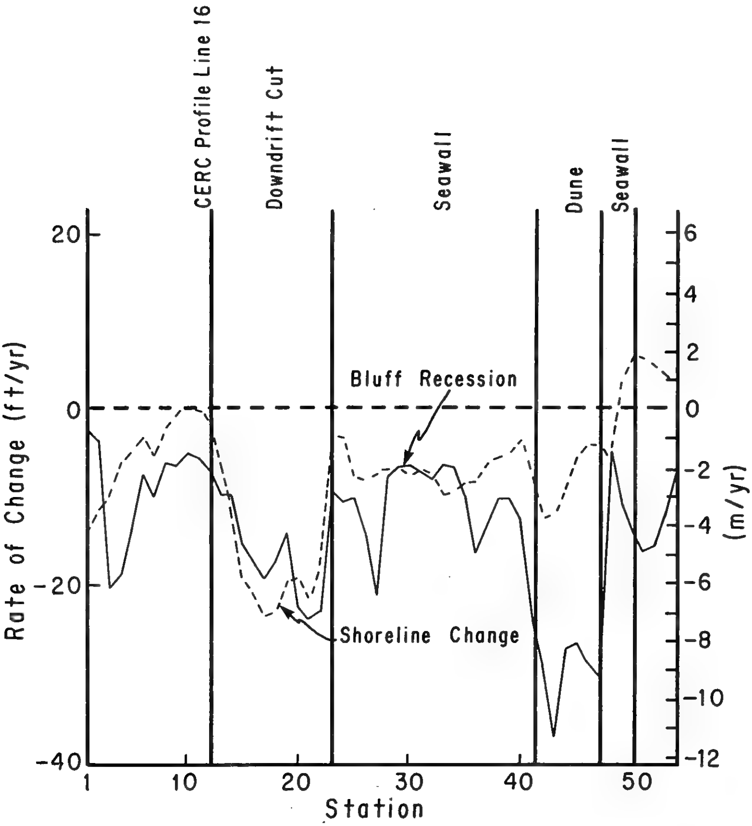

Figure 19. Rates of bluff recession and shoreline change along reach B from 19 November 1970 to 23 November 1974.

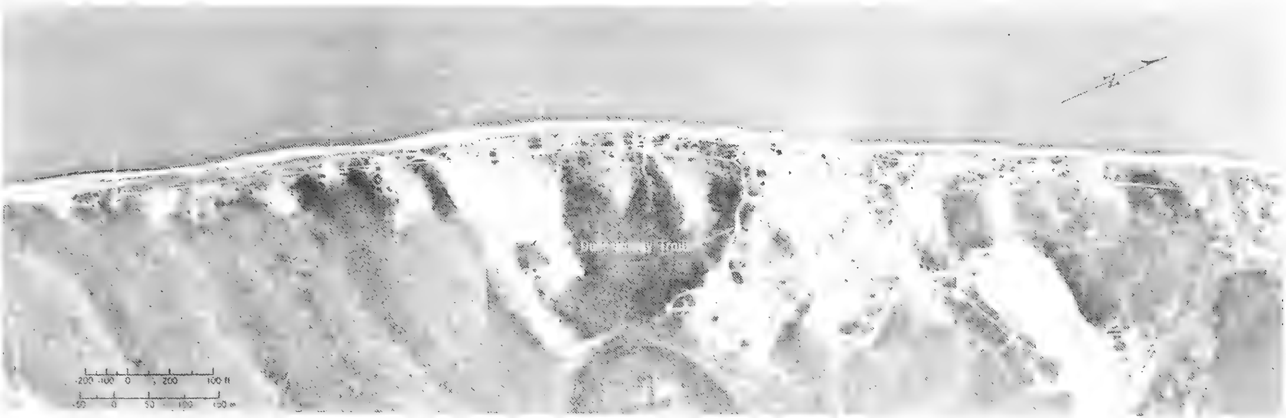

Figure 20. Composite aerial photo of reach C taken 23 November 1974. Note dune buggy trails between stations 30 and 40.

Figure 21. Low foredune topography typical of reach C (17 October 1976).

During the 4-year study period, the most noticeable change in reach C occurred to the inland dunes in the northern part of the reach. Because of the easy access and the rolling topography, the area has become popular with four-wheel drive enthusiasts. The air photos clearly document a widening of the trails and an increase in the number of roads across the dunes. A ground photo of the area is shown in Figure 22. No attempt was made to determine if the increased use of the area had an effect on the rate of bluff recession. The area has recently been closed to vehicular traffic (C.L. Kureth, The Traverse Group, Ann Arbor, Michigan, personal communication, 1979).

Data were taken from the air photos at about 1-year intervals between 15 April 1971 and 23 November 1974. The results of the bluff recession rate and average beach width computations are shown in Figure 23. The shift from accretion to recession occurs between stations 15 and 16 with the bluff or foredune being stable or accreting south of station 15. The average rate of accretion for stations 0 to 16 was 2.0 meters per year; the remaining stations retreated 3.2 meters per year, the lowest rate for any of the reaches. The rate of shoreline change over the 4 years was an almost constant -3.7 meters per year, though the rate was lowest at the ends of the reach.

Although measurements of beach width are of questionable accuracy due to the difficulty in establishing a repeatable landward bound, the beach width data (Fig. 23) correlate well with the bluff recession rates. In general, where the beach was wide, the dune or bluff line either stabilized or accreted; where the beach was narrow, the dunes retreated. During October 1973 to November 1974, the beach width averaged 5.6 meters and was fairly constant along the

Figure 22. Dune buggy trails through the reach C dunes between stations 30 and 40 (17 October 1976).

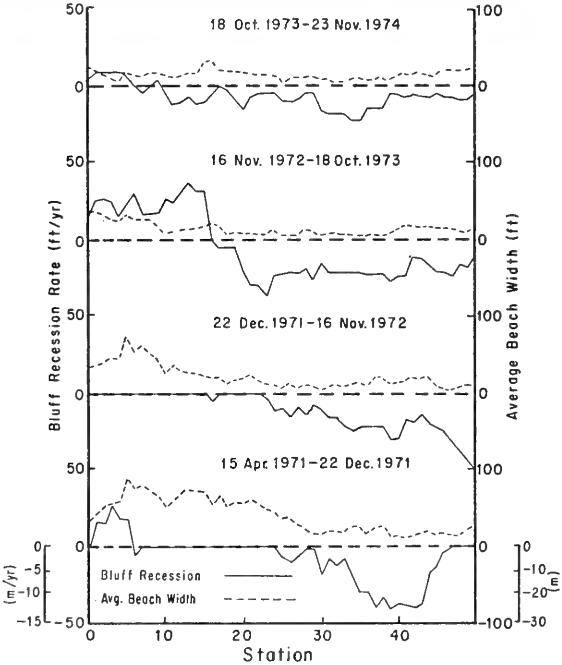

Figure 23. Comparison between the rate of bluff recession and the average beach width along reach C. Note different vertical scales.

reach. During the same period, the bluff recession was also a fairly constant 2.0 meters per year. A simple regression analysis of the average beach width and the recession rate at each station during each period resulted in correlation coefficients of 0.6 or higher except for the last period which had a correlation coefficient of 0.26. This is an indication of the importance of beach width on bluff or, in this case, dune movement. Average rates of bluff recession and shoreline change for the full 4 years are shown in Figure 24. Reach C data are summarized in Table 7.

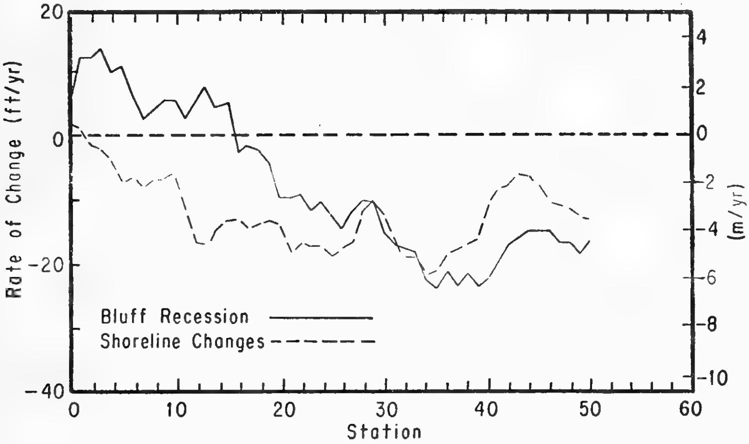

Figure 24. Rates of bluff recession and shoreline change along reach C from 15 April 1971 to 23 November 1974.

Table 7. Summary of bluff, shore, and beach data for reach C (51 stations).

Date	Bluff recession				Shoreline change				Beach width[1]			Period length
	(m)	Rate (m/yr)	σ (m/yr)	Max. (m/yr)	(m)	Rate (m/yr)	σ (m/yr)	Max. (m/yr)	(m)	σ (m)	Change (m)	(mo)
15 Apr. 1971									13.3	9.2		
	1.5	2.2	4.9	12.3	-2.1	-3.1	13.0	31.4				8
22 Dec. 1971									5.9	6.6	-7.4	
	3.3	3.6	4.0	15.0	-7.3	-8.0	6.9	-26.3				11
16 Nov. 1972									5.6	4.1	-0.3	
	1.6	1.7	6.7	11.6	-5.7	-6.3	3.6	-13.0				11
18 Oct. 1973									4.5	2.5	-1.1	
	2.2	2.0	2.4	7.0	2.0	1.9	3.7	9.5				13
23 Nov. 1974									6.6	2.3	2.1	
15 Apr. 1971 to 23 Nov. 1974	8.5	2.4	3.5	7.2	-13.1	-3.7	1.7	-6.6				43

[1] Beach width adjusted to lake level (176.79 meters IGLD).

5. Reach D.

Reach D is located 3.0 kilometers south of the powerplant, inside the area affected by the beach nourishment project. The reach, which includes

54 stations and extends for 1.65 kilometers (Fig. 25), is similar to reaches C and E with a foredune system fronting a higher ridge. The primary difference between reaches D, C, and E is the degree of development of the area. No major shore protection structures were within the reach until the final year of the study when two precast concrete seawalls (see Fig. 18) were placed between stations 4 and 8. Just south of the reach, three groins protect Weko Beach. Although in need of repair, the groins offer some protection to the southern end of the reach. A typical section of reach D is shown in Figure 26.

The effect of the groins is shown in Figure 27. Except for the first period of study the bluff recession dropped to a lower value at the southern stations updrift of the groins. Changes in the bluff line vary considerably along the reach and between time periods.

The average rate of recession between 19 November 1970 and 15 April 1971 was only 2.6 meters per year with a very stable bluff or dune line between stations 22 and 36. The rate dropped slightly to 2.4 meters per year between 15 April 1971 and 16 November 1972 but rate comparisons were difficult because of the different time intervals. Stations 36 to 54 remained unchanged. During the first two periods (19 November 1970 to 16 November 1972), the average amount of bluff recession was 4.8 meters, exactly one-half of the 9.6 meters lost in reach A during the same period.

The situation changed between 16 November 1972 and 18 October 1973 when 7.1 meters of bluff eroded for a recession rate of 7.8 meters per year. A peak rate of 17.4 meters per year occurred at station 5.

The level of recession decreased during the final period between 18 October 1973 and 23 November 1974. Total recession was 4.4 meters for an average recession rate of 4.1 meters per year.

Except for the first period the shoreline changes exhibited the same trends as the bluff recession rates. The largest negative rate of shoreline movement (13.6 meters per year) occurred between 16 November 1972 and 18 October 1973 and accompanied a period of high bluff recession.

The average rates of bluff and shoreline changes for the full 4-year period are shown in Figure 28. The two rates apparently correlate well and generally decrease south to north. The average rate of shoreline change was -3.2 meters per year, less than the average bluff recession rate of 4.1 meters per year. Reach D data are summarized in Table 8.

6. Reach E.

Reach E (Fig. 29) is located within Warren Dunes State Park and is very similar to reaches C and D with an active foredune ridge. A ground photo typical of the area is shown in Figure 30. Reach E includes 54 stations along 1.62 kilometers of shoreline and, like reach C, is undeveloped and without shore protection structures. One feature common to the reach is a periodic undulation of the shoreline described as "beach pads" by Tanner (1975). He postulated that the pads which averaged 145 meters apart provide a mechanism for offshore sand transport. The crests of two small pads are shown in Figure 29.

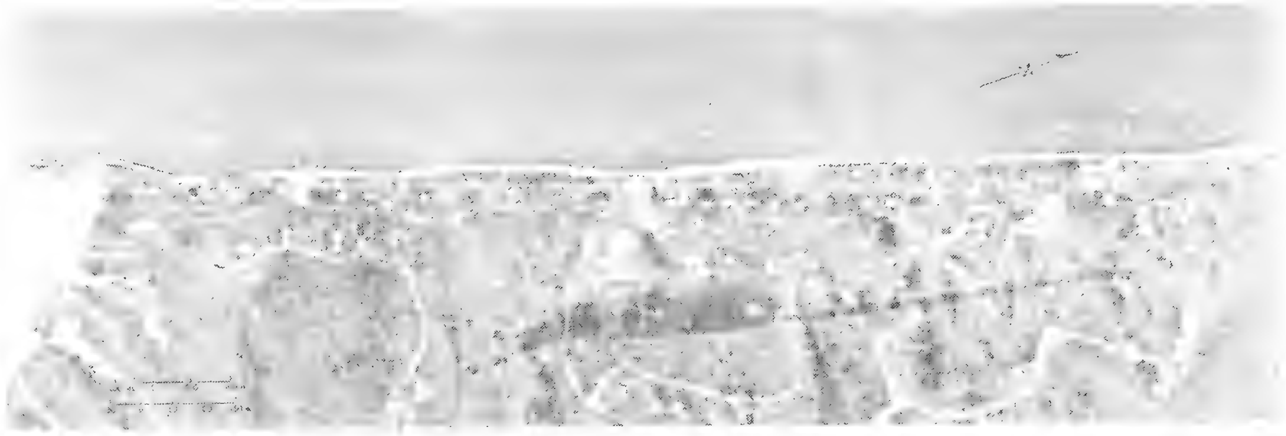

Figure 25. Composite aerial photo of reach D taken 23 November 1974. Arrows indicate the location of shore protection structures.

Figure 26. View of bluff and beach northward from station 27 in reach D (17 October 1976).

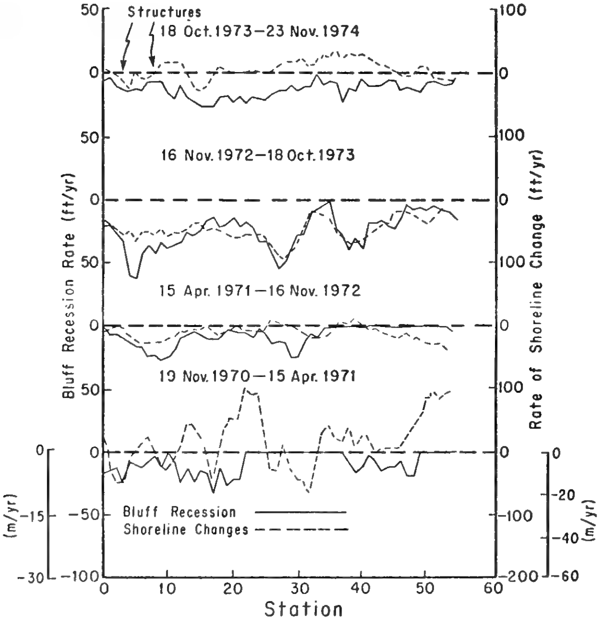

Figure 27. Rates of bluff recession and shoreline change along reach D. Note different vertical scales.

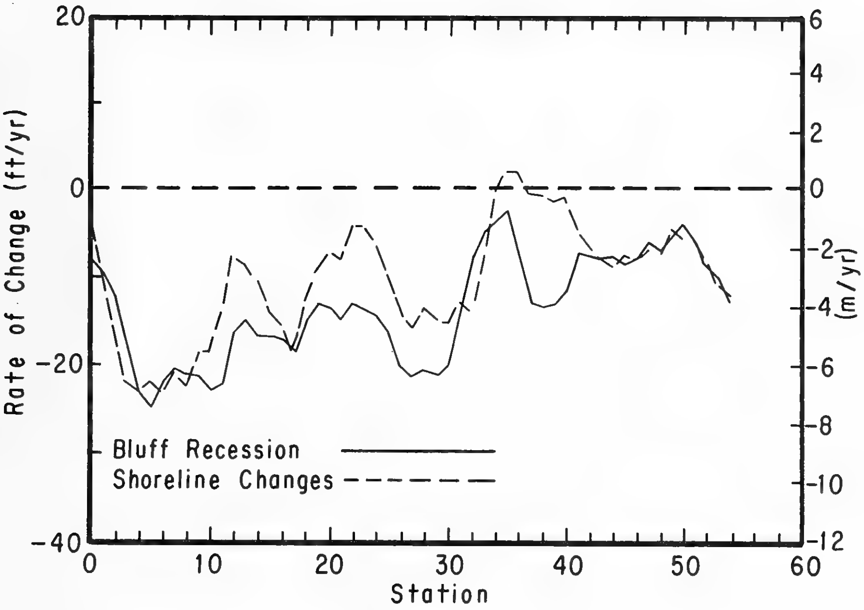

Figure 28. Rates of bluff recession and shoreline change along reach D from 19 November 1970 to 23 November 1974.

Table 8. Summary of bluff, shore, and beach data for reach D (54 stations).

Date	Bluff recession				Shoreline change				Beach width[1]			Period length
	(m)	Rate (m/yr)	σ (m/yr)	Max. (m/yr)	(m)	Rate (m/yr)	σ (m/yr)	Max. (m/yr)	(m)	σ (m)	Change (m)	(mo)
19 Nov. 1970									3.0	3.5		
	1.1	2.6	2.8	10.2	2.5	5.9	13.0	50.7				5
15 Apr. 1971									6.9	4.5	3.9	
	3.7	2.4	2.4	8.3	-4.5	-2.9	3.4	-14.4				19
16 Nov. 1972									7.5	3.1	0.6	
	7.1	7.8	4.3	17.4	-12.5	-13.6	5.7	-28.1				11
18 Oct. 1973									1.8	2.0	-5.7	
	4.4	4.1	2.0	8.2	2.0	1.8	4.7	20.6				13
23 Nov. 1974									9.0	3.1	7.2	
19 Nov. 1970 to 23 Nov. 1974	16.3	4.1	1.8	7.5	-12.5	-3.1	2.0	7.6				48

[1] Beach width adjusted to lake level (176.79 meters IGLD).

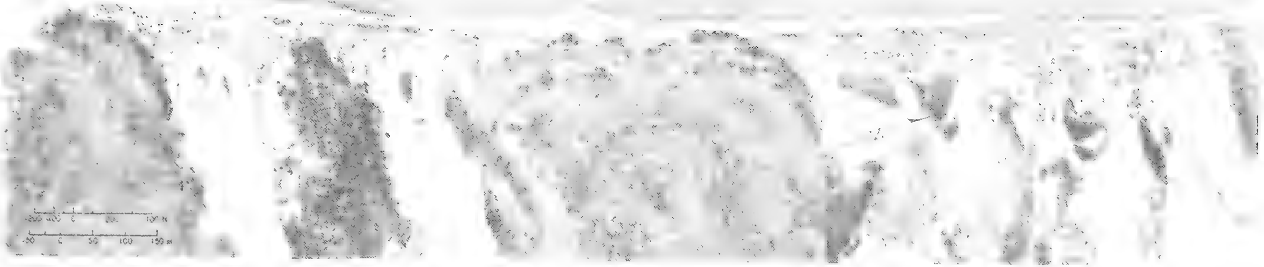

Figure 29. Composite aerial photo of reach E, 23 November 1974.

Figure 30. View southward showing beach and foredune morphology in reach E. Photo taken near station 6 (17 October 1976).

The bluff recession and shoreline change rates for each period are shown in Figure 31. One obvious feature is the regularity in bluff recession rate along the reach, particularly in the first and last period. The only area of high bluff recession was between stations 17 and 26. The recession rate between 15 April and 18 November 1971 was 2.5 meters per year, with a slight increase to 2.8 meters per year during the second period with high localized erosion to both the shoreline and bluff line between stations 18 and 23.

In reach E (like the other four reaches) the bluff recession rate increased significantly during 15 November 1972 to 20 November 1973 but the longshore pattern was similar to the preceding period. The bluff retreated 6.3 meters, an amount greater than the 5.1 meters of recession measured for reach A during the same period. The shoreline accreted 4.7 meters during the period, possibly by the buildup of eroded bluff material on the beach. The rate of bluff recession decreased during the final period to 2 meters per year and was uniform along the reach.

Shoreline changes generally correlated well with the bluff recession during all but the third period. Bluff and shoreline change rates for the full period are shown in Figure 32. Interestingly, the shoreline and bluff-line peaks appear out of phase by six stations.

Beach widths during the study varied from 0 to 25 meters and averaged 10.5 meters. The peak beach widths occurred on the beach pads. The widest beaches occurred 20 November 1973 and averaged 17.0 meters in width. Reach E data are summarized in Table 9.

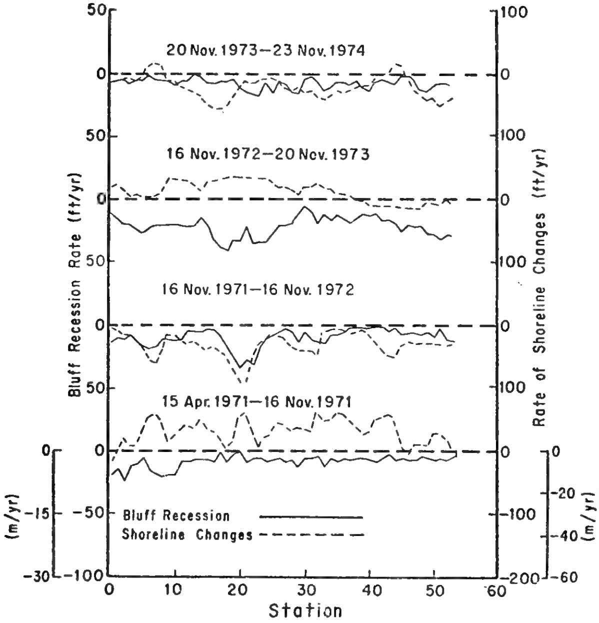

Figure 31. Rates of bluff recession and shoreline change along reach E. Note different vertical scales.

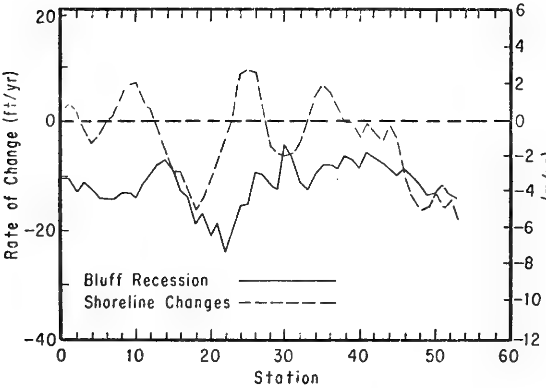

Figure 32. Rates of bluff recession and shoreline change along reach E from 15 April 1971 to 23 November 1974.

Table 9. Summary of bluff, shore, and beach data for reach E (54 stations).

Date	Bluff recession				Shoreline change				Beach width[1]			Period length
	(m)	Rate (m/yr)	σ (m/yr)	Max. (m/yr)	(m)	Rate (m/yr)	σ (m/yr)	Max. (m/yr)	(m)	σ (m)	Change (m)	(mo)
15 Apr. 1971									5.6	3.9		
	1.4	2.5	1.6	7.3	5.9	10.1	6.1	19.6				7
16 Nov. 1971									12.2	3.8	6.6	
	2.8	2.8	2.3	10.1	-8.7	-8.7	5.9	-27.0				12
16 Nov. 1972									7.0	1.4	-5.2	
	6.3	6.3	2.4	12.2	4.7	4.7	4.9	12.3				12
20 Nov. 1973									17.0	5.3	10.0	
	2.1	2.1	1.3	5.2	-5.2	-5.2	5.7	-16.6				12
23 Nov. 1974									10.9	5.5	-6.1	
15 Apr. 1971 to 23 Nov. 1974	12.7	3.5	1.2	7.2	-3.3	-0.9	2.3	-5.56				

[1] Beach widths adjusted to lake level (176.79 meters IGLD).

IV. COMPARISON OF RESULTS

The changes in each reach have been discussed in the preceding section. More detail was given to reaches A and B because of the greater number of photo sets examined. In this section, the results are compared between reaches and to the results of other investigators. In addition, the relationships between the causative factors of bluff recession and the measured rates are examined along with a possible explanation of the effect of the reach B seawall.

1. Comparison Between Reaches.

Cumulative amounts of bluff recession and shoreline change for each reach, as given in Tables 5 to 9, are plotted in Figure 33. The data for four common periods are tabulated in Table 10 for a better comparison of the five reaches. Although reach A had the highest overall bluff recession and bluff recession rate, reach D had the highest rate for any single period, losing 7.1 meters between November 1972 and October 1973. Volumetric losses were definitely larger in reaches A and B due to the greater bluff heights.

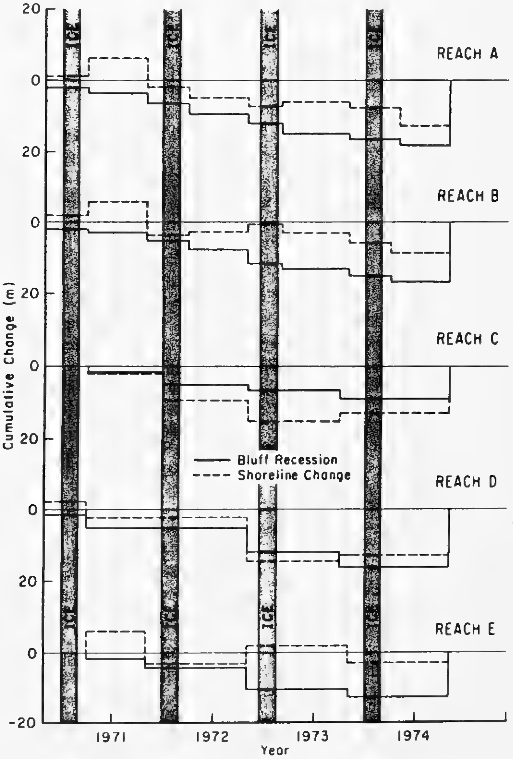

Figure 33. Cumulative bluff recession and shoreline change for each reach (data from Tables 6 to 9). Shaded areas indicate periods of ice cover.

Table 10. Comparison of average bluff recession and shoreline changes for all reaches.

Reach	Period															
	15 Apr. 1971 to 16 Nov. 1972				16 Nov. 1972 (or 18 Oct. 1973) to 20 Nov. 1973				20 Nov. 1973 (or 18 Oct. 1973) to 25 Nov. 1974				15 Apr. 1971 to 23 Nov. 1974			
	Bluff recession		Shoreline chg.		Bluff recession		Shoreline chg.		Bluff recession		Shoreline chg.		Bluff recession		Shoreline chg.	
	(m)	Rate (m/yr)	(m)	Rate (m/yr)	(m)	Rate (m/yr)	(m)	Rate (m/yr)	(m)	Rate (m/yr)	(m)	Rate (m/yr)	(m)	Rate (m/yr)	(m)	Rate (m/yr)
A	7.4	4.7	-5.7	-3.6	5.2	5.2	-1.8	-1.8	3.6	3.6	-6.3	-6.3	16.2	4.5	-13.8	-3.9
B	6.3	4.0	-4.3	-2.7	4.9	4.9	-0.7	-0.7	3.9	3.9	-5.6	-5.6	15.2	4.2	-10.6	-3.0
C	4.8	3.0	-9.4	-5.9	1.6[1]	1.7	-5.7[1]	-6.2	2.2[1]	2.0	2.0[1]	1.9	8.6	2.4	-13.1	-3.7
D	3.7	2.3	-4.5	-2.9	7.1[1]	7.7	-12.5[1]	-13.6	4.4[1]	4.1	2.0[1]	1.9	15.2	4.2	-15.0	-4.2
E	4.2	2.7	-2.8	-1.8	6.3	6.3	-4.7	-4.7	2.1	2.1	-5.2	-5.2	12.7	3.5	-3.3	-0.9
Avg.	5.3	3.3	-5.3	-3.3	5.0	5.2	-3.2	-3.5	3.2	3.1	-2.6	-2.6	13.6	3.8	-11.2	-3.1
Period length (yr)	1.58				1(0.92)[1]				1(1.08)[1]				3.58			
Avg. lake level (m)	176.67				176.91				176.89				176.79			

[1] Refers to period beginning or ending with 18 October 1973.

The lowest overall recession occurred in reach C--the result of the lakeward movement of the foredune in the second period. If the stations where the accretion occurred are not included, then the overall retreat rate increases from 2.4 to 3.2 meters per year, very close to the overall rate for reach E of 3.5 meters per year. Even though the bluff recession rate for reach C was low, the rate of shoreline change was the third highest, averaging -3.7 meters per year. Most of this shoreline movement occurred during the first period.

The changes during the second period are difficult to interpret. In general, the recession rate peaked during this period and then decreased in the final year. This did not, however, occur in reach C where the bluff at the southern end accreted, thereby reducing the average recession rate.

The lowest rates of both shoreline change and bluff recession occurred between the fall of 1973 and November 1974 with similar recession rates along reaches A, B, and D and in reaches C and E. Interestingly, the average recession rate along reach B, even with the long seawall in place, slightly exceeded the reach A rate. Average recession for all reaches over the full period was 13.6 meters for a rate of 3.8 meters per year. The associated shoreline change was slightly less.

Comparing the recession rates north and south of the powerplant, the rates were higher (to the north) in the first period (April 1971 to November 1972), lower in the second period (November 1972 to October or November 1973) and about equal in the third period (October or November 1973 to November 1974). In view of the different characteristics of the reaches, these differences (positive and negative) are insignificant and it is unlikely that they can be attributed to the construction of the temporary harbor. This agrees with the findings reported by Johnson and Hiipakka (1976).

2. Previous Berrien County Erosion Studies.

Numerous studies have been conducted on Great Lakes shorelines. Primary topics include studies of geomorphology, sediment characteristics, and bluff or shoreline changes. A number of these studies have dealt with bluff recession in Berrien County.

A comprehensive study by Powers (1958) classified the entire Lake Michigan shoreline according to geomorphology (bluff type, composition, and height). He also relocated section lines where old bluff-line measurements had been made and determined the rate of bluff retreat. Of 134 stations around the lake, Powers reported that 124 eroded an average of 0.45 meter per year, 4 had no change, and the remaining 6 accreted an average of 0.48 meter per year. Periods of coverage varied from 20 to 127 years.

Powers also recognized lake level fluctuations, severe storms, and manmade structures as primary factors affecting the recession rate. However, he noted the paucity of measurements needed to quantify the relationship between lake level and bluff recession.

Powers (1958) reported that the shoreline in Berrien County consisted primarily of 3- to 12-meter-high bluffs and 6- to 38-meter-high dunes, that the beaches averaged 9 to 49 meters wide, and that the average bluff recession rate for points in Berrien County between 1830 and 1956 was 0.60 meter per year, which was higher than the overall lake average. None of his points were within the five study reaches.

A report on a proposed beach nourishment project for St. Joseph, Michigan, included an analysis of the bluff recession within the five reaches and a study of the bluff, beach, and nearshore sediment characteristics (Beach Erosion Board, 1956). The report concluded that only 20 to 40 percent of the bluff material was suitable beach-fill material. A peak bluff recession rate of 3.21 meters per year was found in reach D for the period 1830 to 1872. The average rate between 1830 and 1954 for all five reaches was only 0.50 meter per year, a value similar to but lower than that derived by Powers (1958) for about the same period.

Seibel (1972) examined the bluff recession since 1938 at four Lake Michigan and two Lake Huron locations, and the relationship between lake level and precipitation, and between lake level, storm frequency, and bluff recession. He determined linear relationships between average lake level and bluff recession for each of the six sites.

One of the six sites was at Bridgeman in Berrien County where measurements were made at 27 profile lines, including six within the five study reaches. Data were obtained from aerial photos dated 1938, 1950, 1955, 1960, 1967, 1970, and 1972. Average bluff recession rate was 1.2 meters per year between 1938 and 1970, although individual profiles retreated as much as 9 meters per year.

In addition to the long-term rates, Seibel also computed the rate of bluff recession between 1970 and 1972 at 14 points near the powerplant from the same photos used in this study. An average rate of 2.8 meters per year was determined, an increase over the preceding period (1967 to 1970). Most of the increase occurred south of the powerplant. Seibel indicates that much of the increase can be explained by the increase in average lake level. An important conclusion reached by Fox and Davis (1970), Seibel (1972), and Johnson and Hiipakka (1976) was the significance of infrequent, severe storms in controlling the rate and amount of bluff recession.

Because the problem of lakeshore property insurance is directly linked to the recession rate in an area, there is considerable interest in predicting future bluff lines for at least the mortgage life of a structure (generally 30 years). Jannereth (1974) described the State of Michigan's effort to predict bluff lines from 1938 and 1974 photos. The results (Michigan Department of Natural Resources, 1975) indicate that except for a small part of reach E, all five reaches are in high risk erosion areas. A bluff recession rate of 1.1 meters per year was determined for reaches A, B, and C, and a rate of 0.5 meter per year for reaches D and E. These values were used to compute a minimum setback line equal to 30 times the recession rate. A recommended setback line was also determined by adding another 9 meters to the minimum setback value.

The Michigan Department of Natural Resources (1974) participated with the U.S. Army, Corps of Engineers in monitoring the effect of the temporary harbor at the powerplant. They found similar rates of recession north and south of the plant at areas with similar bluff topography for the period July 1970 to

June 1974. The average bluff recession rate for 27 points north of the plant and 25 points south of the plant, independent of other factors, was 3.86 meters per year, a value equal to that found by this study. Individual recession values varied from a low of 0.8 meter per year to a high of 7.0 meters per year.

This average rate was also similar to the 3.9 meters per year measured by Tanner (1975) for the period 1970 to 1973 using the same aerial photos (specific measurement locations were not given). A higher rate of recession (4.2 meters per year) was determined for the same area between 1964 and 1970. Tanner presented an exponential relationship between bluff retreat and lake level, wave characteristics, and other unspecified parameters.

Long- and short-term bluff recession rates reported in various sources are summarized in Table 11. To better illustrate the different time periods considered, they are shown in Figure 34 along with variations in annual lake level since 1860. A major decrease in the long-term average lake level occurred around 1890 due primarily to changes in the outflow conditions of the Lake Huron Basin (Brunk, 1968). Though the effect of this change on bluff recession rates is difficult to assess, the data of Powers (1958) and Beach Erosion Board (1956) should be affected. The high levels before 1890 may also account for the peak recession rate of 3.21 meters per year measured near reach D by the Beach Erosion Board for the period 1830 to 1872. The overall bluff recession rate of 3.8 meters per year determined by this study (Table 9) and by both Tanner (1975) and the Michigan Department of Natural Resources (1974) is higher than the 2.65 meters per year reported by Seibel (1972) for a shorter period between 1970 and 1972.

All of the annual rates determined for the five reaches are higher than the long-term rates of about 0.55 meter per year reported by Powers (1958) and Beach Erosion Board (1956). It is interesting that the long-term recession rates increased from 0.55 to about 1.1 meters per year when the period changes from 1830 to 1954 or 1956 (125 years) to 1938 to 1970 or 1974 (34 years). This doubling of the recession rate may be an indication of a general increase in bluff recession in recent years.

From the data in Table 11 an engineer, developer, or land manager could legitimately estimate bluff recession using a long-term rate between 0.5 and 1.2 meters per year. Over a 30-year period, the implied recession would be between 15 and 36 meters. For comparison, station 99 in reach A lost 30 meters of bluff during this study alone. Consequently, even the selection of the higher rate may not provide a suitable buffer zone. This situation is further proof of a lack of understanding of the bluff recession phenomena and the usefulness of a particular recession rate value. The lack of predictable lake level and storm cycles is another complicating factor. Since either lake levels or severe storm frequency cannot be predicted with any confidence for a long enough period, it is impossible to determine a priori whether to use a high or low recession rate.

Cohn and Robinson (1976) attempted to predict lake levels by Fourier analysis of historic lake level records between 1860 and 1970. They were able to determine prominent cycles of 1, 8, 11, 22, and 36 years. The model correctly predicted the rise in lake level between 1970 and 1975 and forecasted a general decrease in lake levels between 1975 and 1980. Peak lake levels are expected in 1985 and 1993.

Table 11. Summary of bluff recession rates reported in various sources.

Location	Time interval	Average lake level (m)	Recession rate (m/yr)
Powers (1958)			
Berrien County	1830-1956	------[1]	0.60
Lake Michigan (all)	1830-1956		0.45
Beach Erosion Board (1956)			
Reach A	1830-1954	------[1]	0.44
Reach B	1830-1954		0.25
Reach C[2]	1830-1954		0.05
Reach D[2]	1830-1954		1.28
Peak	1830-1872		3.21
Reach E[2]	1830-1954		0.49
Avg. (all reaches)	1830-1954		0.50
Seibel (1972)			
Bridgeman, Mich.	1938-70	176.11	1.17
	1938-50	176.08	0.75
	1950-55	176.49	1.48
	1955-60	176.05	1.41
	1960-67	175.88	0.73
	1967-70	176.30	2.78
Near nuclear powerplant	1967-70	176.30	1.95
	1970-72	176.54	2.78
Michigan Department of Natural Resources (1974; 1975)			
Reaches A, B, and C (1975)	1938-74	176.25	1.1
Reaches D and E (1975)	1938-74	176.25	0.5
Near nuclear powerplant (1974)	1970-74	176.71	3.86
Peak	1970-74		7.0
Minimum	1970-74		0.8
Tanner (1975)			
Near nuclear powerplant	1927-56	176.15	0.64
	1956-64	175.95	2.5
	1964-70	176.05	4.2
	1970-73	176.67	3.9

[1] Insufficient data; no lake level data collected between 1830 and 1860.

[2] Actual stations near but not in these reaches.

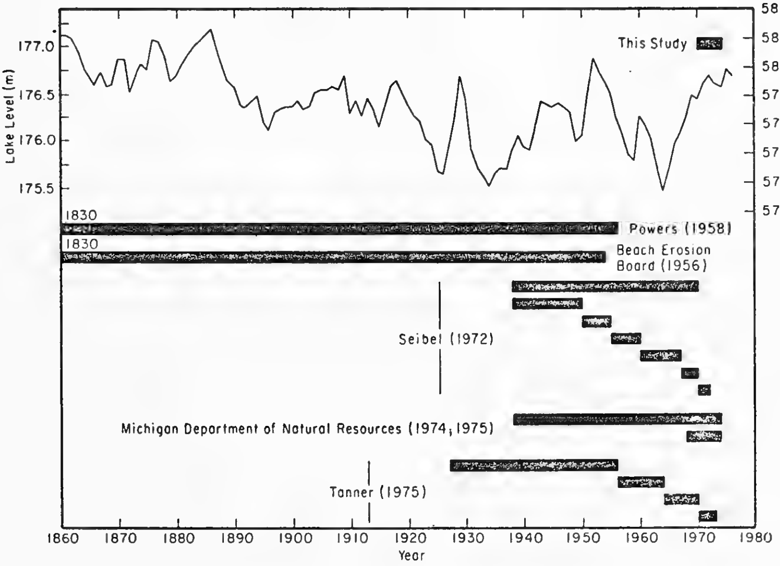

Figure 34. Periods of previous study and historic lake level variations.

3. Prediction of Bluff Recession.

As discussed previously, Seibel (1972) determined a linear relationship between average lake level and bluff recession. His bluff recession rate measurements (Table 11) correlated well with the average lake level for each period (correlation coefficient of 0.73), explaining about 50 percent of the variance. Seibel also considered the average number of storms in each period which was fairly constant and did not correlate well.

Since this study includes more detailed measurements over shorter time periods, these relationships were reexamined using simple and multivariant regression analysis. With bluff recession rate, B, as the dependent variable, linear relationships with the following independent variables for each period were examined:

AL = average of daily lake levels during each period.

RL = average rate of lake level change computed from monthly average lake levels.

HL = average of the highest 1/4 daily lake levels.

W = percent of time that winds were onshore ($220^\circ < \theta < 20^\circ$) and greater than 26 kilometers per hour as measured at the Muskegon, Michigan, airport (the nearest weather station 137 kilometers to the north).

The selection of some variables was arbitrary and the results may have possibly been improved, for example, by increasing or decreasing the cutoff windspeed. However, this was not done since the intent was only to identify the important variables, not to develop the best possible prediction equation.

The data were refined by assuming that all bluff recession occurred during the ice-free periods. Therefore, storms and lake levels during the ice-covered periods were not considered and the value of each variable was computed based on the length of the ice-free periods using the estimated periods of ice cover given in Section II,5. (Note: all rates of bluff recession discussed previously have considered the entire period regardless of ice cover.) Only data from reach A were considered because of its lack of major structures and the fact that eight recession rate measurements were made in the reach. These data in final form are given in Table 12.

The reduction in period length due to ice cover caused a significant increase in the winter recession rates which accentuated the already high winter values compared to the lower summer rates. This is the inverse of the lake levels which are high in the summer and low in the winter.

Figure 35 shows the relationship between the variables, including the actual variations in the mean monthly lake level, the mean monthly rate of lake level change, and the number of days per month that onshore windspeeds

Table 12. Reach A recession and process data used in linear regression model.

Date	Bluff recession		Average lake level	Avg. rate lake level change	Avg. high 1/4 lake levels	Time period onshore winds >26 km/hr	Period length	Estimated ice cover
	Amount (m)	Rate (m/yr) B	(m) AL	(m/yr) RL	(m) HL	(pct.) W	(d)	(d)
19 Nov. 1970								
	2.15	10.6	176.48	-0.12	176.54	16	74	74
16 Apr. 1971								
	1.44	2.5	176.66	0.05	176.72	3	214	--
16 Nov. 1971								
	2.79	12.9	176.51	-0.18	176.57	12	79	74
17 Apr. 1972								
	3.22	5.6	176.75	0.44	176.84	1	211	--
16 Nov. 1972								
	2.55	18.6	176.78	-0.31	176.81	16	50	70
20 Mar. 1973								
	2.58	3.8	176.97	0.03	177.06	4	245	--
20 Nov. 1973								
	1.74	5.2	176.81	0.32	176.91	7	121	60
20 May 1974								
	1.91	3.7	176.94	-0.48	177.09	5	187	--
23 Nov. 1974								
Correlation coefficient[1]			-0.41	-0.39	-0.49	0.87		

[1] Correlation coefficient resulting from linear regression with the bluff recession rate as dependent variable and independent variables.

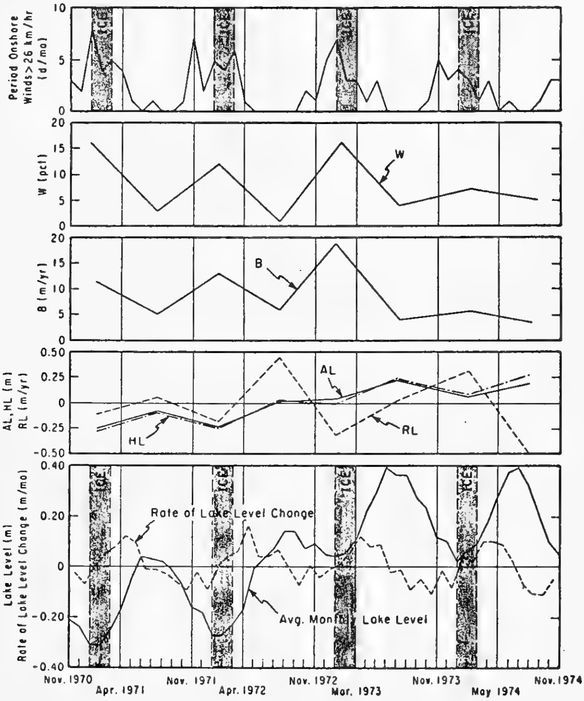

Figure 35. Variations in the variables (defined in Table 12) used in the regression analysis. Actual monthly variations in period of onshore winds, lake level, and rate of lake change are also shown. (Note: all lake level values are plotted around the mean value from November 1970 to November 1974.) Vertical lines denote photo dates and ice periods.

exceeded 26 kilometers per hour. Clearly, only W has the right phase and amplitude variations as the bluff recession rate, B. Simple regressions between B and the other variables yielded the correlation coefficients given in Table 12. Interestingly, although the rate of bluff recession correlated well with W (correlation coefficient = 0.87), explaining 76 percent of the variation, it negatively correlated with all of the lake level variables.

Attempts were made to obtain better correlation by combining variables and by multivariate analysis, but no significant increase was found in the correlation coefficient above 0.87. More meaningful conclusions might be possible if the data were further refined and the data set expanded.

One of the weakest variables is W, which estimates storm wave activity during a period. Muskegon, Michigan, data were used because of the uniform quality, but hourly data taken at the powerplant indicate different and generally higher values. The powerplant wind data were not used because of gaps in the data and because of problems in resolving which of two anemometers (at different elevations) were used.

Since the ultimate interest is in the wave action and energy reaching the beach, wave data (either actual or hindcasted) should be included. Unfortunately, the Warren Dunes State Park LEO data did not cover a long enough period to be useful. Quigley (1976) examined the relationship between the bluff recession rate and wave power on Lake Erie and found a strong linear correlation (r = 0.79). However, he proposed a more realistic, nonlinear, relationship involving the combined effects of low and high waves and varying lake levels.

Other problems with the data in Table 12 which may affect the correlations include the different period lengths, the incomplete knowledge of ice periods, and the imperfect split of the storm periods since the effect of September and October storms fall into the longer summer periods. Another study of the aerial photos (or a similar set) should make more frequent measurements (every month or every other month) and should include a monitoring program of waves, ice, and lake levels.

Though the lake level variables did not correlate well with the bluff recession rates in Table 12, its importance on bluff recession is well known. Berg and Collinson (1976) showed that there is a phase lag between bluff recession and lake levels. Part of the reason for the lag is the time required to denude bluffs of protective vegetation as the levels rise and the time needed to revegetate the bluffs after the levels start falling. In this study with its unique point in the lake level cycle (a rising peak), the bluffs within reach A were already actively eroding at the beginning of the study and the lag effect may not be significant. The average lake level steadily increased to its peak and then stabilized at a high level while the recession generally increased until 1974 when it dramatically decreased.

The computations of the lake level variables in Table 12 were based on average values for each ice-free period. If the average lake level, AL, is shifted one period forward to improve the phase relationship with B, the correlation coefficient between B and AL changes from -0.41 to 0.01. No increase occurred in the correlation coefficient between B and W when the shifted AL was included as a third variable.

The actual monthly variation in the rate of lake level change was periodic during the study; therefore, the true effect of the average rate of lake level change during each study period is difficult to identify using photos spaced at regular intervals each year.

The value of the regression exercise is to identify the importance of short-term storm effects (as indicated by W) on the bluff recession rate.

To test Seibel's (1972) linear relationship between average lake level and long-term bluff recession rates, the average changes for all reaches over the four periods (Table 10; ice days included) were combined with data from other sources (Table 11). The results (Fig. 36) further support a strong lake level dependence.

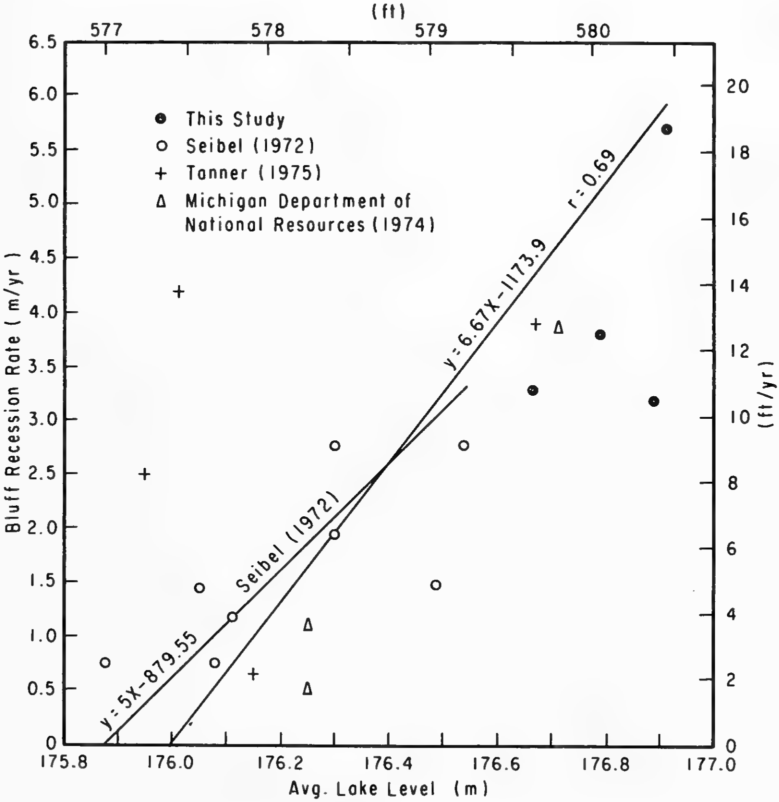

Figure 36. Effect of lake level on the bluff recession rate (data are from Tables 10 and 11).

A simple regression analysis of average lake level and bluff recession rate for the 19 data values resulted in a correlation coefficient of 0.69, explaining about 50 percent of the variance. The intercept of the trend line shifts to the right and the slope is steeper than that found by Seibel (1972). The shift is due primarily to the high rates of recession reported by Tanner (1976) for two relatively low lake levels.

These two points are important to the overall lake level bluff recession relationship and may be explained by the lake levels shown in Figure 2. A rate of 2.5 meters per year was recorded between 1956 and 1964, a period of generally falling lake levels except for a sharp rise of 0.46 meter between 1959 and 1960. It is speculated that much of the recession occurred during this period. The other point was a 4.5-meter per year recession rate between 1964 and 1970, a period of low average but rapidly rising lake levels.

The two data points are important because they indicate that high rates of recession can occur during low lake levels and that other factors than average lake level need to be considered.

4. Explanation of Seawall's Effect.

A seawall protects the shoreline by separating land and water areas with a fixed boundary. Because of high wave reflectivity off vertical and sloping seawalls, the rate of erosion tends to increase in front of the seawalls and it is difficult to maintain a fronting beach. According to the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977) the ground at the toe of a seawall, bulkhead, or revetment can be expected to scour below the natural bed to a depth equal to the height of the maximum unbroken wave which can be supported in the original water depth.

Similar guidelines are not available for the effects on the shore adjacent to the seawall, although the SPM cautions that when a seawall is built on a receding shoreline, the recession on adjacent shores will continue and may be accelerated. The three-dimensional aspect of seawalls has been discussed by Silvester (1972; 1974; 1977). Silvester (1977) describes a seawall as a means of protecting a shoreline which is receding due to an imbalance between the supply of sediment and the sediment-carrying capacity of the incoming waves. While the construction of a seawall will protect the land behind it, it only accentuates the original problem by further reducing the supply of littoral material to the unprotected region of the beach. This is actually what is occurring downdrift of the long seawall in reach B.

Silvester (1977) also theorizes that the interference of incident and reflected waves produces a short-crested wave system which increases the transport of material in front of and immediately downdrift of a seawall over what would have normally occurred without the wall. Farther downcoast, this excess sediment can no longer be carried and it settles out as a shoal.

In the specific case of the reach B seawall, the shoal did not appear on any of the air photos, but the lack of a beach within the downdrift cut and the occurrence of a beach farther downcoast offer some support to the Silvester theory.

During a visit to the area in October 1976, longshore currents were measured using dye as a tracer. A minor storm was then occurring from the northwest with wave heights of 1.2 meters and periods of 7 seconds. The water depth along the seawall increased from 1.4 meters at the northern end to 1.7 meters near the southern end of the wall. Because of this depth, waves were not breaking before striking the seawall. Longshore current measurements taken about 2 meters from shore at stations 14, 28, and 44 (see Fig. 9) are given in Table 13. The southward-moving current was about twice as fast near the southern end of the seawall as north of it, and more than three times faster than the current just south of the downdrift cut where the beach begins. Therefore, the current is capable of moving more sediment at the downdrift end of the seawall than it is either updrift of the seawall or south of the downdrift cut. Although the amount of material moved depends on the width of the current, its effectiveness is clearly evident in the complete absence of a beach in front of the seawall.

Table 13. Longshore current measurements in reach B, 16 October 1976.

Station	m/s	ft/s
44 (north of seawall)	0.30	1.0
28 (along seawall)	0.58	1.9
14 (south of seawall)	0.18	0.6

According to Silvester (1977), the effect of the seawall should be localized between the shoal and the downdrift end of the wall. In this specific case, the affected beach appears to be lengthening, partly because of the measures taken to stabilize the cut and partly because of the reduced sediment supply caused by the wall.

Using the aerial photo data, the volume of material lost in the downdrift cut was estimated and compared to the volume of material removed from the sediment supply by the seawall. The computations (Table 14) are based on the period between 20 March 1973 and 23 November 1974 when the seawall was completed, the backing bluff had stabilized, and the beach in front had disappeared. Expected rates of recession for the seawall and downdrift cut were computed from the recession of reach A during the same period but were adjusted by a factor based on the relative recession rate between each section and reach A in 1971, before the seawall was constructed. Therefore, the expected rate for the downdrift cut is low relative to reach A. Average elevations for each section were subjectively determined from topographic maps and a few ground measurements.

Table 14. Comparison of volumetric losses behind and adjacent to seawall.

Section	Station	Elevation[1] (m)	Length (m)	1971 bluff recession (m)	Factor[2]	Bluff recession rate 20 Mar. 1973 to 23 Nov. 1974 (m/yr)		Total volume change 20 Mar. 1973 to 23 Nov. 1974 (m^3/yr)		
						Expected	Actual	Expected	Actual	Difference
Reach A	51 to 111	12	1,646	3.6	1.0	4.6	4.6	90,859	90,859	0
Dune	42 to 46	13	152	8.1	2.3	10.6	3.1	20,946	6,126	-14,820
Seawall	23 to 41	12	579	2.9	0.8	3.7	1.5	25,708	10,422	-15,286
Downdrift cut	14 to 22	9	274	0.8	0.2	0.9	9.1	2,219	22,441	20,222
	1 to 13	7	396	1.8	0.5	2.3	3.6	6,376	9,979	3,603
Total										- 6,281

[1] Estimated from topographic maps and some field data.

[2] Ratio of the recession rate of each section to the reach A rate for November 1970 to November 1971.

NOTE.--Ratio of volume differences: downdrift cut (stations 1 to 22) to dune and seawall (stations 23 to 46) 23,825/30,106 = 0.8.

Interestingly, the bluff continued to erode behind the seawall but at a rate 40 percent lower than the estimated rate without the seawall. This further recession was probably caused by wave and spray overtopping, by slumping of the bluff, and by waves flanking the ends of the seawall. The material eroded in this manner either filled in behind the seawall or contributed to the littoral drift supply.

The reduction in loss to the dune area is intriguing since it sustained extensive erosion in the early years of the study. One explanation is that the two seawalls adjacent to the dune acted like artificial headlands while the beach in between evolved into a stable, crescent-shaped embayment (Dean and Maurmeyer, 1977).

During the same period, the two sections downdrift of the seawall experienced a 380-percent increase in the volume eroded compared to the volume change expected based on the recession rate in this area before the seawall was constructed. The actual increase in volume equaled about 80 percent of the decrease in volume of the dune and seawall sections due to the seawall. This one case study does not prove the theory that the additional amount of material eroded from the shores adjacent to a seawall will approximately equal the amount of material removed from the sediment supply by the seawall, but it does indicate that such a relationship may exist.

Because no new material is being added to the system, the downdrift erosion can be expected to continue, though probably at a reduced rate depending on storm frequency, lake level, and the effectiveness of measures to mitigate the erosion.

V. SUMMARY

1. Results.

This report has dealt specifically with the bluff recession which occurred in Berrien County, Michigan, near the Donald C. Cook Nuclear Plant between 1970 and 1974. Though site specific, some of the findings and the analysis procedures used are applicable to other areas and studies. A major difference between this study and others which have used aerial photos to measure bluff recession is the quality and large scale of the aerial photos. Errors were minimized by the selection of the best sets from the monthly photos in terms of flight path, vegetation, ice cover, waves, offshore bars, and shadows. Measurement distances were kept short and interpretation errors were reduced by using stereo images to define the bluff.

Measurements to the bluff line, bluff toe, and shoreline were made every 30.5 meters and bluff changes were computed to an accuracy of ±1.4 meters (see App.). An adequate measure of the bluff recession rate for a receding reach of shoreline over a 1-year period could be obtained with as few as 20 equally spaced measurements per 1.6 kilometers (App.). The number reduced to 10 for measurements over a 4-year period. Even fewer may be adequate for longer periods.

The bluff and shorelines of all of the five reaches eroded significantly during the study. The average rate of bluff recession was 3.8 meters per year while the shoreline retreated 3.1 meters per year. Individual measurement points lost considerably more with the bluff at one station in reach B receding an average of 11.9 meters per year for a total loss during the study of 47.6 meters.

Bluff recession rates were the greatest along reach A where the sandy bluff was high, unvegetated, and unprotected. Because of the higher bluff, volumetric losses were also greatest along reach A. The lowest bluff recession rates were measured at the two undeveloped reaches (C and E). Reach C had the lowest rate with some of the dune accreting. The average recession for the points that eroded was similar to the average loss along reach E. The highest average rate of recession occurred during the period that included a severe storm (March 1973).

By using close measurements points, it was possible to illustrate the high degree of spatial variability in bluff recession rates. Generally, when the amount of bluff recession increased, the standard deviation increased. Over 1-year periods the standard deviations of the rate of bluff recession varied from 1.3 meters per year along reach E to 6.7 meters per year at reach C.

Rates of shoreline change were generally greater than the bluff recession rates with considerably more spatial variation. Because of relief displacement and the difficulty in accurately accounting for the effect of a changing lake level on the shoreline, shoreline measurements were less accurate than bluff recession measurements.

During the study period, the average recession rate for all the reaches (Table 9) increased along with the lake level, peaking in 1973 (the year of the major storm) and then decreased in 1974 when the lake level stabilized and no major storms occurred.

Because these data cover a relatively short period at a unique point in the lake level cycle (the rising side of a peak lake level), the effect of lake level cycle could not be definitively determined from the photos examined in this study. Long-term lake level effects were examined by combining the data in Table 10 with the findings reported in various sources. This resulted in evidence of a lake level dependency with average lake level explaining about 50 percent of the variation in bluff recession rates.

Although many important variables affect the rate of bluff recession, a very simplistic linear regression approach was used to identify the relative importance of lake level and short-term storm events (indicated by the percentage of occurrence of high onshore windspeeds). For the eight available data points from reach A, the only significant correlation was found for the short-term events. This relationship is shown in Figure 35. More data points are needed over a wider range of conditions in order to examine the effects of other variables like wave climate, bluff type, bluff height, orientation, ice, etc.

An important aspect of this study is the analysis of the effect of the long seawall constructed during the period within reach B. A general expression for the relationship between seawall length and the volume and length of the affected shoreline cannot be made from only one example; however, the data in Table 14 indicate that such a relationship may exist. It was determined that the additional volumetric loss of the bluff adjacent to the downdrift end of the seawall approximately equaled the amount of material removed from the sediment supply by the seawall. The length of shore affected increased during the study and appeared to be still increasing in 1976 as attempts were made to stabilize the eroding area.

2. Further Research.

This study has concentrated primarily on obtaining measurements of bluff and shoreline changes. The aerial photos are, however, limited in providing details on bluff composition, runoff effects, and other features; therefore, the importance of these factors cannot be examined without detailed ground surveys. Most States now have programs to determine long-term recession rates (see Great Lakes Basin Commission, 1974; Michigan Department of Natural Resources, 1975; Berg and Collinson, 1976; Carter, 1976).

Further research should be directed toward obtaining a better and more complete record of bluff recession and the complex factors controlling it. This requires a well-planned program of ground surveys coupled with aerial photos.

Sites should be carefully chosen to include various bluff and shoreline conditions and a reasonable number of cultural features for reference points. Although the aerial photos can easily cover long stretches of shore, only short reaches need to be analyzed. Accurate ground control can be established by ground surveys coupled with contour maps compiled from aerial photos. Measurements should be taken at minimum intervals of 1 year and after major storms. Monitoring should continue through one full lake level cycle (20 to 25 years) and preferably longer.

A complete and consistent record of the wave energy reaching the beach is also necessary. Wave hindcasting is probably the most cost-effective means for obtaining this information. Accurate observations of ice cover are also required along with lake level measurements.

This type of program is necessary to fully understand the relationship between lake level, storms, and bluff recession. It is particularly important if attempts are made to minimize shore erosion by lake level regulation.

The systematic long-term research program outlined above would provide considerable insight into these long- and short-term relationships. This type of effort is necessary to develop confidence in an ability to predict future Great Lakes bluff and shoreline changes.

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APPENDIX

ANALYSIS PROCEDURE

Various procedures are currently in use for making measurements from aerial photos. Therefore, it is important to discuss the procedure and to estimate the accuracy before attempting to understand the results.

1. Photo Measurements.

One commonly used procedure for taking measurements from aerial photos is to make measurements from carefully selected low elevation reference points to the feature being studied (Stafford, 1971). The reference point must be a clearly defined stable feature which appears on all the sets of photos. After all the measurements have been made and scaled according to each photo, changes can be computed. The primary advantage of this method is that measurements are taken directly from the photo. The disadvantage is that points of measurement cannot be taken at equal intervals along the shoreline and it cannot be used in areas with few cultural features; also, since measurements are made independently, problems in defining the bluff line may cause it to move lakeward, a physical impossibility. This is particularly true when the time intervals are short and the bluff line is relatively stable.

A second procedure involves a form of indirect measurement where photo details are optically transferred to a base map by a device like a zoom transfer scope (ZTS). Wilson and Everts (in preparation, 1980) provide an example of this method.

The ZTS allows magnification, rotation, and stretching of one image to superimpose the image on another. It is, however, difficult and tedious to use. For this reason, Istvan (1974) recommends that the ZTS should not be used to determine shore and bluff recession because of optical errors, the difficulty of matching photos precisely, and the greater potential for interpreter error and fatigue.

A combination of these procedures was used in this study to optimize speed and accuracy. Measurements to the toe of the bluff and the shoreline were made directly on each photo using an appropriately scaled grid of the reference line and the station locations. This procedure was considered accurate enough to identify shoreline and beach width variations.

Greater accuracy was desired for the bluff line. Using an acetate overlay, the bluff line on each photo was traced with the aid of a scanning stereoscope. Using the ZTS, the photo with the bluff-line overlay still in place was then superimposed on the corresponding November 1974 photo by matching the center part of the photo. (The ZTS was only used to match the scales; the "stretch" feature was not used.)

After the photos were matched, the bluff line was transferred to an acetate overlay on the November 1974 photos. In this manner, the bluff lines could be compared as they were being drawn and errors due to photo interpretation were reduced.

After all the bluff lines were drawn, a grid of the reference line and station locations was placed on the November 1974 overlay and measurements to each bluff line from each station were made. This procedure also eliminated problems in relocating the reference line from photo set to photo set.

2. Sources of Error.

The straightforward estimation of distance from aerial photos is based on several convenient assumptions which are not often satisfied practically. Errors can be separated into those which are inherent in the photo and those which are due to the analysis procedure. The various sources of error are well known and frequently discussed (Thompson, 1966; Stafford, 1971; Istvan, 1974; Stoker, 1976; Tanner, 1978). Compensation for some errors may be possible if enough information is available. An estimate of the magnitude of the maximum and most probable error for the procedure used is developed below.

Photo errors are due to relief displacement and scale variations within single photos, between photos in a set, and between sets. Since other errors are scale-dependent, their effects have to be combined in any procedure where measurements are made directly on the photos (Istvan, 1974).

By using the above procedure, variations in scale among photos in a set or between sets were virtually eliminated (relative to other errors) by optically matching the photos to the November 1974 set.

The assumed accuracy of the scale used for the November 1974 photos was verified by the actual ground measurements shown in Table A-1. Objects with well-defined end points were selected without regard for elevation or orientation. The amount of error ranged from 0 to -1.43 meters; the average absolute error was 0.5 meter. Relative errors varied from -3.6 to 4.2 percent, averaging 0.03 percent.

Table A-1. Comparison between actual and photographic measurements.

Object	Approximate elevation (m above LL)	Distance (m)		Error (m)	Relative error (pct)
		1974 photos	Actual		
Distance between two groins	1	18.29	18.66	-0.37	-1.98
Seawall	1	33.53	32.92	+0.62	1.88
Swimming pool	12	19.81	19.72	+0.09	0.46
Roof	11	27.43	26.82	+0.61	2.27
Seawall	1	49.38	49.99	-0.61	-1.2
Seawall	1	38.10	39.53	-1.43	-3.6
Seawall	1	35.05	34.90	0.15	4.2
Tennis court	9	45.72	45.26	0.46	1.02
Tennis court	9	36.58	36.42	0.16	0.44
Between lines in parking lot	6	18.29	18.29	0.0	0.0
Seawall	1	33.53	34.14	-0.61	-1.79
Seawall	1	29.26	29.87	-0.61	2.04
Roof	9	21.34	21.49	-0.15	0.70
Avg. of absolute values				0.49	1.66
Avg.				-0.13	0.03

Scale variations within a single photo are due to changes in ground elevation and the amount of tilt of the image relative to the ground. For an image parallel to the ground, the scale of the photo can be expressed as

$$S = \frac{f}{H} \qquad \text{{A-1)}$$

where f is the focal length of the camera lens and H is the height of the camera above the ground. Since the scale varies for points of different elevation, the scale for a point at an elevation h above the general ground elevation can be written as

$$S = \frac{f}{H - h} \qquad \text{(A-2)}$$

The problem is compounded when the image is tilted relative to the ground at an angle σ. Then equation (A-2) becomes

$$S = \frac{f - y \sin \sigma}{H - h} \qquad \text{(A-3)}$$

where y is the radial distance measured on the photo from the nadir or center of the photo to the point of interest. As seen from equation (A-3), the effect of tilt is to linearly modify the scale in a direction perpendicular to the axis of tilt. The effect of tilt can be minimized through the optimal matching procedure described. With enough information, tilt can be eliminated by rectifying the photos. According to Tewinkel (1962) about 50 percent of all aerial photos are tilted less than 2° and very few more than 3°.

A reasonable estimate of the effect of tilt and topographic relief can be determined from equation (A-3). Starting with equation (A-1) and using the known focal length and nominal scale of

$$f = 0.152 \text{ meters}$$

$$S = 1{:}3{,}600$$

a value of H can be determined.

$$H = 547.2 \text{ meters}$$

Using the data in reach A as an example, the following average and maximum values of the variables in equation (A-3) were determined. Estimated variations in the elevation of the bluff line within a single photo (h, actual) are

$$h_{avg} = 3 \text{ meters}$$

$$h_{max} = 5 \text{ meters}$$

Distance from station to nadir (y on photo)

$$y_{avg} = 0.0381 \text{ meter}$$

$$y_{max} = 0.0889 \text{ meter}$$

Then, using a conservative tilt estimate of 2°, the following maximum scale error was determined.

$$S_{max} = \frac{0.152 - 0.0889 \sin 2°}{547.2 - 5} = \frac{1}{3,641}$$

$$\Delta S_{max} = S - S_{max} = \frac{3,600 - 3,641}{3,600} = 1.1 \text{ percent}$$

Similarly, using average values and 2° of tilt, an average scale error can be computed

$$\Delta S_{avg} = \frac{3,611 - 3,600}{3,600} = 0.3 \text{ percent}$$

Because these errors were minimized by the procedure used, ΔS_{avg} is probably the more realistic error. This amount of error can be converted to distance, D, by using the maximum distance measured between the reference line and the bluff line (52 meters).

$$\Delta D_{min} = 0.03 \times 52 = 1.56 \text{ meters}$$

Therefore, a reasonable assumption is that the amount of error for a single measurement will lie between + 1.56 and - 1.56 meters and be normally distributed about a zero mean. A consequence of this assumption is that 99.7 percent of the errors for all measurements lie within three standard deviations of the mean error. The standard deviation of the error, σ_t, can then be estimated as 1/6 of the total range, or in this case

$$\sigma_t = 2 \times \frac{1.56}{6} = 0.52 \text{ meter}$$

and the variance

$$\sigma_t^2 = 0.27 \text{ square meter}$$

Another error inherent in vertical aerial photos is relief displacement. Figure A-1 shows that the location of the top of an object of height h will appear to be farther from the nadir than it actually is. This difference in distance, dR, depends on both the height of the object, h, and its radial distance from the nadir, R. The amount can be calculated as

$$dR = R \frac{h}{H} \qquad \text{(A-4)}$$

Relief displacement is an important error in any area that has considerable relief, e.g., the bluffs. However, the procedure used allowed relief displacement errors to be neglected. This was possible because of the optical matching and because the reference line was selected close to the bluff line and at a similar elevation. Since the quantity of interest is the amount of bluff recession, calculated as the difference between two measurements at a single station, the only source of relief displacement error affecting this quantity is a change in position of a measurement station, relative to the nadir, between photo sets. Even this is minimized by using reference points near the bluff to optically match the photos.

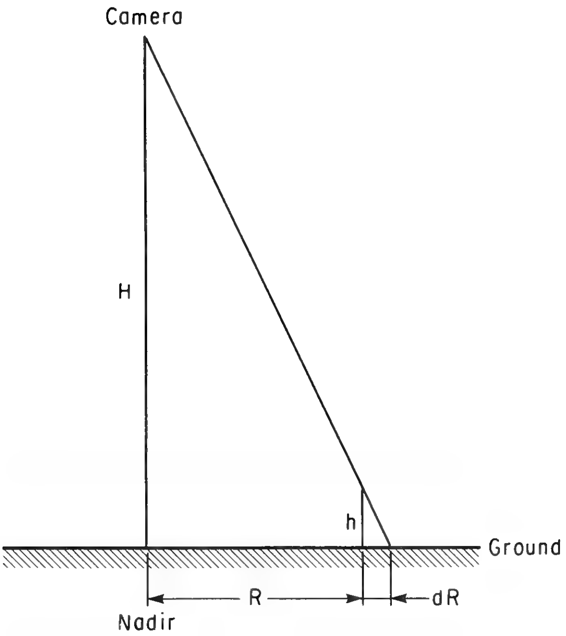

Figure A-1. Effect of relief displacement.

An estimate of the probable error in the radial displacement between the reference line and the bluff line at a station was computed for the average quantities given above and was found to equal only 0.23 meter. This was for a single measurement and the actual effect for successive measurements can be assumed to be considerably less. Because the bluff line was usually displaced west from the nadir, relief displacement is always a positive effect and unlike scale variations, it cannot be assumed to follow a normal distribution.

A major source of error which is difficult to quantify is that resulting from interpretation and human error. These errors occur from improper interpretation of the various beach and bluff features, improper photo matching, and careless measurements. Photo interpretation is a tedious process and should be recognized as such. Errors can be minimized by careful photo selection, by using the simplest possible procedure, and by including frequent checks and remeasurements.

Analysis errors resulted from inaccurate bluff-line identification and transfer and from the accuracy of the measuring device. Because all bluff measurements were made on the November 1974 photos, the errors are independent of scale variation errors. Moreover, since the errors are random, it can be assumed that they have a zero mean and that the amount of error follows a normal distribution. These assumptions allow the standard deviation of the error to be estimated by following the procedure previously used for scale variations due to tilt and relief.

Measurements were made using an engineer's scale with 24 divisions per centimeter (60 divisions per inch). This allows an accuracy of 1/2 division which at the photo scale equals ±0.76 meter. Therefore, the effect of measurement error, e_m, can be determined by estimating the standard deviation σ_m.

$$e_m = \pm 0.76 \text{ meter}$$

$$\sigma_m = \frac{1.52}{6} = 0.25$$

$$\sigma_m^2 = 0.064$$

The errors in identifying and marking the bluff line, e_b, and in transferring it to the 1974 photo set, e_z, are unique to the analysis used in this study. The width of the ink line is 1.5 meters and the line is drawn so that one edge of the line traces the bluff line. To minimize interpretation errors, photos were selected at times when trees were without leaves and when the bluff line was well defined.

If a conservative error of ±1.5 meters is assumed for each process, then

$$e_b = e_z = \pm 1.5 \text{ meters}$$

$$\sigma_b = \sigma_z = \frac{3.0}{6} = 0.5$$

$$\sigma_b^2 = \sigma_z^2 = 0.25$$

Finally, collecting all the error terms

$$\sigma^2 = \sigma_t^2 + \sigma_m^2 + \sigma_b^2 + \sigma_z^2$$

$$\sigma^2 = 0.27 + 0.064 + 0.25 + 0.25 = 0.834$$

$$\sigma_d = 0.91 \text{ meter}$$

Therefore, individual distances from the reference line to the bluff line can be measured to an accuracy on the order of ±1 meter. This is a reasonable amount of error which has been kept small by (a) a large photo scale (1:3,600), (b) short measuring distances, (c) optical matching of photos, and (d) with all photos at the same nominal scale.

The accuracy in determining bluff-line changes can also be determined by

$$\delta = D_2 - D_1$$

where

δ = change in bluff line

D_1 = measured distance at time $t = t_1$

D_2 = measured distance at time $t = t_2$

$V(\delta) = \sigma_{D_1}^2 + \sigma_{D_2}^2$ = variance of δ

Since the nominal scale of all the photos was the same, and since the distances were approximately equal,

$$\sigma_{D_1}^2 \simeq \sigma_{D_2}^2 = 0.91$$

$$V(\delta) = 0.91 + 0.91 = 1.82$$

$$\sigma_\delta = 1.35 \text{ meters}$$

Therefore, a change in bluff position can be determined to an accuracy of ±1.35 meters. This error is quite large and makes it difficult to measure small amounts of change.

In bluff recession rate determinations, the accuracy improves for long-period data and decreases for short periods. For example, a bluff recession amount of 20 ± 1.4 meters over 4 years reduces to an annual rate of 5 ± 0.3 meter per year.

Measurements were also made to the toe of the bluff and the shoreline. The accuracy of these measurements is considerably less than for the bluff measurements because of increased relief displacement and line definition problems. Changing water levels also affected the accuracy of shoreline measurement and of comparing successive measurements.

Stoker (1976) reported on the difficulty of properly identifying the various beach and bluff features out to the offshore bar and indicated that interpretation was the major source of error.

3. Number of Measurement Stations.

The errors given above pertain to one station and are too large to detect small changes in bluff recession rates; therefore, measurements were taken every 30.5 meters. This allows mean changes to be specified as small as $\pm\sigma/\sqrt{n}$ (defined as the standard error of the mean) where n is the number of stations and σ is the standard deviation of the rate of bluff change. For example, using the bluff recession along reach A for four 1-year intervals (see Table 5), the mean recession rate varied from 3.6 to 6.0 meters per year with the standard deviation varying from 1.9 to 3.8 meters per year. With 57 stations within the reach, those values give a standard error between ±0.3 to ±0.5 meter per year. An empirical evaluation was made to determine the minimum number of stations needed to obtain a mean recession rate which was within ±0.3 meter per year of the mean value determined using all stations. This was done by first removing the linear trend from the 1- and 4-year recession rate data from reach A. Subsamples of n stations were then obtained by systematically sampling (Cochran, 1963) all the stations at equal increments of k stations such that $nk \simeq 57$. For each year and for each value of k, k unique subsamples were obtained. Means were calculated for each subsample and the maximum difference between sample mean $(\bar{x}_s)$ selected from the set of $4 \times k$ subsample and the population mean $(\bar{x}_{57})$ was plotted versus the number of stations in a sample (see Fig. A-2). The figure also shows a similar line (based on k samples) computed for a rate per year using data over a 4-year interval which has a significantly lower standard deviation than the 1-year data.

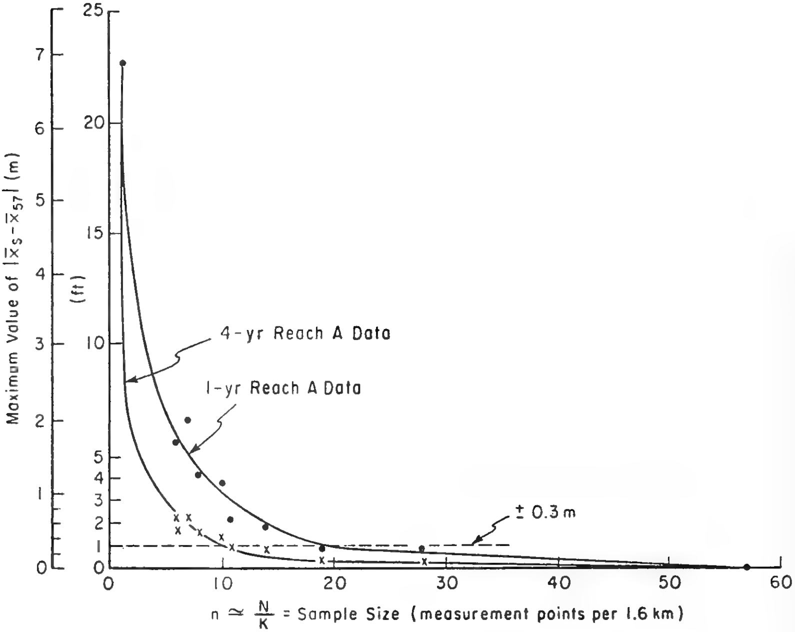

Figure A-2. Comparison of maximum difference between $\overline{x}_s$, the mean bluff recession rate of a sample of n equally spaced measurements per 1.6 kilometers, and $\overline{x}_{57}$, the mean computed for all 57 stations. Lines are shown for 1- and 4-year periods (curves are hand-fit).

From Figure A-2, it appears that for data from 1-year periods, 20 measurement stations at equally spaced increments per 1.6 kilometers would result in a mean recession rate within ±0.3 meter per year of the value which would be determined using 57 stations. This amounts to a 65-percent reduction in the number of measurements needed.

Since Figure A-2 is based on the maximum difference between $\overline{x}_s$ and $\overline{x}_{57}$ (instead of the mean difference), it should be conservative.

Fewer stations are needed for longer period data as indicated by the shift of the line for the 4-year data to only 10 stations required for the same accuracy. If an accuracy of ±0.3 meter per year is inadequate, Figure A-2 can also be used to select a larger sample size.

This rather simplified procedure for estimating measurement station frequency is presented for general guidance in setting up a similar study. The actual number of stations needed will vary depending on the quality and scale of the air photos, the time period considered, the accuracy desired, the uniformity of bluff type, and the analysis procedure. It is suggested that some experimenting be done with measurement density along a short reach of coast before a final station frequency is selected.

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